OPTIMAL INCENTIVE/DISINCENTIVE DETERMINATION

BETWEEN COST AND BENEFIT

A Thesis

by

PIYUSH SHARMA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Kunhee Choi
Committee Members,	Edelmiro Escamilla
	Jun Hyun Kim
Head of Department,	Joe Horlen

August 2013

Major Subject: Construction Management

ABSTRACT

In an effort to motivate contractors to complete construction projects early on high-impact highway pavement construction projects, state transportation agencies (STAs) including TxDOT have often used incentive/disincentive (I/D) contracts. However, determining I/D rates is extremely difficult due largely to the lack of systematic methods for helping STAs determine effective I/D rates. The primary goal of this project is to develop a novel framework for determining the most realistic and economical I/D dollar amounts for high-impact highway improvement projects. To achieve its goal, this project proposes an integration analysis including project schedule and the lower and upper bounds of the I/D contract. The lower bound is the contractor's additional cost of acceleration, and the upper is the total savings to road users and to the agency.

The study data were gathered using Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software. These data were then grouped by four different types of pavements, namely Joint Plain Concrete Pavement (JPCP), Continuously Reinforced Concrete Pavement (CRCP), Hot Mix Asphalt (HMA), and Milling and Asphalt Concrete Overlay (MACO). With these data, a series of regression analyses were carried out to develop predictive models for the validation of time-cost tradeoff to determine I/D lower bound. Road user cost and agency cost savings were quantified using CA4PRS to develop lookup tables to determine I/D upper bound. Adjustment of contractors' additional cost of acceleration with Level of Service (LOS)

and total savings adjustment using Net Present Value (NPV) were incorporated in the research study to calculate point based estimates of I/D for lower and upper bound, respectively. Lastly, case studies on real world projects were conducted to evaluate robustness of the model. The research results reveal that the predictive models give appropriate results for the case studies in determining the I/D dollar amount for the lower and upper bound.

This study will provide the research community with the first view and systematic estimation method that STAs can use to determine the most economical and realistic I/D dollar amount for a given project–an optimal value that allows the agency to stay within budget while effectively motivating contractors to complete projects ahead of schedule. It will also significantly reduce the agency’s expenses in the time and effort required for determining I/D dollar amounts.

DEDICATION

Dedicated to my family members and all my friends

Ravinder K. Sharma

Sangeeta Sharma

Isha Sharma

ACKNOWLEDGEMENTS

I would like to express my gratitude and whole-hearted thanks to my committee chair, Dr. Kunhee Choi, for his encouragement, insightful directions and guidance over the course of this research study. I would also like to extend my sincere thanks to my committee members, Dr. Edelmiro Escamilla and Dr. Jun Hyun Kim, for their invaluable advice and comments throughout the course of this research. I strongly believe that I was able to improve my thesis work and extend my knowledge further due to their insightful comments and constant motivation I received from them.

Especially, I would like to send my sincere thanks to the Southwest Region University Transportation Center (SWUTC), Texas A&M University, from where I received resourceful funding during the course of this research study. Finally, I am grateful to my parents for their tireless support and endless love, and wish them the very best for their good health and spirit.

NOMENCLATURE

AADT	Annual Average Daily Traffic
AC	Agency Cost
ACP	Asphalt Concrete Pavement
ADT	Average Daily Traffic
AEC	Agency Engineering Cost
ARRA Act	American Recovery and Reinvestment Act
CAC	Contractors' Additional Cost
Caltrans	California Department of Transportation
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
COZEEP	Construction Zone Enhanced Enforcement Program
CRCP	Continuous Reinforced Concrete Pavement
DOTs	Department of Transportation
FHWA	Federal Highway Administration
HMA	Hot Mixed Asphalt
I/D	Incentive/Disincentive
JPCP	Jointed Plain Concrete Pavement
LLPRS	Long Lasting Pavement Rehabilitation Strategies
LOS	Level of Service
MACO	Milling and Asphalt Concrete Overlay
MCM	Movable Concrete Barrier

NPV	Net Present Value
RUC	Road User Cost
SHAs	State Highway Agencies
STAs	State Transportation Agencies
SWUTC	Southwest Region University Transportation Center
TxDOT	Texas Department of Transportation
VOC	Vehicle Operating Cost

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

1 INTRODUCTION AND BACKGROUND

1.1 Current Highway Construction Paradigm

According to the Federal Highway Act of 1956, majority of the highway construction projects were built in the 1950's through 1970's and are still in service while receiving little or no rehabilitation, and at the same time carrying two to five times the originally estimated traffic volumes (Uhlmeyer and Russell 2013). Many of the pavements on these highways have far exceeded their original 20-year design lives because traffic demand has been greater than initially anticipated, and have become seriously deteriorated which makes driving on the roads less safe and affects motorists' comfort, safety and vehicle operating costs negatively (Lee et al. 2006). The estimated annual costs to road users, businesses, and transportation agencies caused by highway construction traffic delays totaled $43 billion in 1998 (Edwards and Orfali 1998) and the estimated total loss because of road traffic injuries in the US was a staggering $230 billion in the year 2002 (Scurfield et al. 2004). Hence there is an increased need to rehabilitate the deteriorating highways not only from the financial stand to tackle the losses, but also taking into consideration the safety of the motorists.

1.2 Status of Transportation Infrastructure Renewal

In recent years, many state departments of transportations (DOTs) have implemented a larger number of highway rehabilitation projects in virtually every state in the United States which differ fundamentally from new highway construction projects in that they require an uninterrupted flow of traffic throughout both the duration and geometric length of the project (Lee et al. 2006). The paradigm shift from new construction projects to renewal of already existing deteriorated projects is the result of increased needs to provide the traveling public with economical, efficient and safe modes of communication.

However, the recent economic recession has created a poor financial status in many state governments which has made it impossible to increase governmental expenditures for infrastructure recovery projects. As a response to the rapid economic downturn faced by the United States especially in the infrastructure sector, the American Recovery and Reinvestment Act (ARRA) legislation was brought into practice under which the state DOTs received a funding of $36.6 billion (Honek et al. 2011). The Federal highway Administration (FHWA) was the major recipient and received approximately $27.5 billion (Winston and Langer 2006) to be invested in highways, bridges, and other federal highway infrastructure programs, apart from the Federal Aviation Administration (FAA, $1.1 billion), and the Federal Railroad Administration (FRA, $8 billion) (Orndoff and Papkov 2012).

1.3 Alternative Accelerating Contracting Concepts: Incentive/Disincentive

In order to minimize inconvenience to the traveling public, thereby reducing the risk associated with lengthy travel times and congested traffic flows, State Transportation Agencies (STAs) must come up with contacts methods to reduce overall construction/rehabilitation time. One such innovative contracting strategy applied on a widespread basis these days in reducing the inconvenience to the motorists and thereby reducing public expenses because of delays, is the use of Incentives/Disincentives. l/D provisions are used in construction contracts to reduce contract cost, to minimize contract duration, and to maintain acceptable levels in the safety, productivity, technological progress, innovation, management efficiency, and quality of construction (Arditi and Yasamis 1998). The Code of Federal Regulations defines an incentive/disincentive (I/D) for early completion as “a contract provision which compensates the contractor a certain amount of money for each day identified critical work is completed ahead of schedule and assesses a deduction for each day the contractor overruns the incentive/disincentive time” (Sun et al. 2013). The basic concept of the I/D contracting strategy is to motivate the contractor to work faster, plan ahead and schedule accurately, and manage the construction process in a holistic manner. More than 35 State Transportation Agencies (STAs) have implemented I/D contracting provisions and have reported substantial project time savings on many projects (Choi and Kwak 2012).

2 PROBLEMS AND SETTINGS

2.1 Gaps in Existing Knowledge

Agencies use various contracting methods to reduce user delays, such as A + B bidding, A+B+C bidding, lane rental and completion time incentives/disincentives (I/D). In an effort to motivate contractors to complete construction projects early on high-impact highway pavement construction projects, state transportation agencies including TxDOT have often used incentive/disincentive (I/D) contracts. Early completion incentives have been shown to be an effective way to motivate contractors to use innovative methods to complete projects early. I/D is one of the most widely used alternative contracting strategies to accelerate construction while minimizing traffic inconvenience to the traveling public, adjoining communities, and business enterprises. For instance, I/D provisions have been applied to 15 percent of all highway improvement projects in Texas. The I/D contracting rewards contractors with bonuses for early completion of projects and levy fines for delays.

The amount of compensation specified in I/D contracts not only affects contractor project performance, but it also reflects how a DOT spends taxpayer money. To encourage competitive contractors to bid on projects, an agency must offer I/D amounts greater than the contractor's additional cost of acceleration while keeping overall costs low enough to prevent strains on project budgets. DOTs have mostly determined I/D rates by their impacts on road user cost, as measured as savings or in delays. However, this has often resulted in frequent misapplications. Determining I/D rates that promote early completion of projects, exceed contractor's additional cost of acceleration, but are below the total cost savings realized by the agencies, is extremely difficult. Contractors' reluctance to disclose pertinent cost data is part of the problem, but the larger issue is that there is no systematic method and tool for helping DOTs determine effective I/D rates.

Critical information needed to determine the agency benefits and additional contractor resource requirements and associated cost is the accurate estimation of optimized production rate. Hence it is crucial to determine two very important things:

1. The STAs must be able to effectively encourage the contractors to finish critical civil transportation projects ahead of the schedule by offering time-based incentives. It is imperative on the part of the STAs to use sound methods to optimize contractors' additional cost to complete the projects in case of time bound I/D projects. The additional cost of acceleration to complete the projects ahead of time in this study is defined as the lower bound.
2. The STAs must come up with measures to optimize savings in terms of road user cost (RUC) and agency cost (AC), generated as a result of completing the project ahead of schedule i.e. in a time-based manner. The total savings generated by combining both RUC and AC in this study is defined as the upper bound.

The relation between the above mentioned two points (lower and upper bound) can be described using the equation

$$CAC \leq I/D \leq (\text{Savings in terms of RUC} + AC)$$

I/D amount should always be greater than the contractors additional cost for expediting construction in order to motivate them to bid for critical projects. At the same time, implementation of I/D provision increases the projects costs to the contracting agencies but it is generally observed that the net savings in terms of RUC and AC is much higher than the overall cost of expediting the rehabilitation work (Choi and Kwak 2012; Pyeon and Lee 2012). Hence, the I/D amounts should always be less than the portion of the decrease in total time savings (RUC and AC) for cutting construction times (Choi 2008).

2.1.1 Problem I: Lack of Proper Techniques to Optimize I/D Effectively

Alternative contracting strategies such as I/D are project specific and although many state DOTs have adopted these strategies, guidelines used for the creation of I/D contract parameters are under development, not fully established, and are often instituted ad-hoc rather than through a generally defined set of principles (Sillars and Leray 2006). Problem specifically arises when the agencies have to estimate the right I/D amount taking into consideration cost growth from the contractors' side and benefits attained from road user cost and agency cost savings. In most of the cases, the agencies rely on the experience of the engineers to determine contract times and value of the road user delay (Herbsman et al. 1995; Shr and Chen 2004). Hence it is very difficult to predict the most realistic I/D dollar amount in case of critical civil infrastructure projects. There is ineffectiveness to predict the appropriate discounting factors in order to determine most realistic I/D dollar amounts.

2.1.2 Problem II: Lack of Standardized Methods and Analytical Tools

Most state DOTs do not have established standard procedures or specific policies to set up reasonable I/D amounts in general with given project constraints (Pyeon and Lee 2012). In the current scenario, it is very difficult on the part of the STAs to calculate point based estimates of I/D by taking into account contractors' additional cost of acceleration and benefits in terms of road user cost and agency cost, concurrently.

2.2 Research Objectives

The primary objective of this project is to develop a novel decision-support framework that determines the most realistic and economical I/D dollar amounts for time-critical highway improvement projects. To achieve this objective, this study has the following five distinct sub-objectives:

- Gather preliminary information and identify gaps in knowledge.
- Develop comprehensive time-cost tradeoff data from stochastic simulations sourced from real-world highway pavement rehabilitation projects.
- Develop stochastic models for the lower bound estimate of I/D.
- Develop a stochastic model for the upper bound estimate of I/D.
- Validate research results.

2.3 Research Methodology and Hypothesis

To achieve the objectives, this study involves a simulation-based stochastic approach that concurrently captures schedule, contractors' additional cost of acceleration, and total savings to road users and to the agency by combining existing schedule and traffic simulations with a stochastic analysis. This section is described in the form of following steps:

1. **Gather preliminary information and identify gaps in knowledge**: This task will provide the research team with a preliminary assessment of current state-of-the-practice with I/D provisions.
2. **Develop comprehensive time-cost tradeoff data from stochastic simulations sourced from real-world highway pavement rehabilitation projects**: This task will provide comprehensive time-cost tradeoff data for use in developing a stochastic model that estimates contractor's additional cost of acceleration (lower bound of I/D). In this task, schedule simulations will be carried out using an innovative software tool called Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) based on contractors' actual construction plans sourced from real-world construction projects. These simulations will generate schedule compression trend data that model the relationship of "time-cost tradeoff" on four different levels of resource use; that is, ordinary, 5 percent increase, 15 percent increase, and 25 percent increase in the number of resources per hour per team. Changes in cost in response to schedule compression will then be calculated based on a cost manual published and updated annually by TxDOT (or RSMeans unit price information). A set of contractors' time-

cost tradeoff data will be created on the four different resource usage levels by calculating changes in cost in response to schedule compression.

3. **Develop Stochastic Models for the lower bound estimate of I/D**: In this task, the relationship between time and cost will be plotted from the time-cost tradeoff data to determine an appropriate initial regression equation and a regression analysis will then be carried out to create a prediction model that determines the contractor’s additional cost of acceleration (lower bound of I/D dollar amount).
4. **Develop a stochastic model for the upper bound estimate of I/D**: This task will produce a stochastic model that estimates the total savings achieved for road users and the agency by accounting for heterogeneity of drivers’ value of time. The proposed new methods incorporate driver’s value of time as heterogeneous along with project schedule, contractors’ additional costs, and uncertainties in other key parameters. This task will also incorporate a Bayesian approach assuming unknown parameters to have distributions into jointly modeling I/D as a function of road user cost, contractor’s additional cost of acceleration, and other uncertain variables.
5. **Validate research results**: In this task, the robustness of the proposed framework’s reliability in estimating optimal I/D rates will be validated through several case studies with TxDOT’s actual incentive projects by looking at prediction errors.

2.3.1 IDEF0 Modeling Tool

Icam DEFinition for Function Modeling (IDEF0), where 'ICAM' is an acronym for Integrated Computer Aided Manufacturing, technique was used to highlight the stepwise procedure aimed at arriving optimal I/D dollar amount. The robustness of the proposed framework was validated with the help of case studies.

Integration Definition (IDEF0) was first developed by ICAM program in 1981, which is a functional model used to describe the processes or systems within an organization (Liu and Hu 2011). The modeling tool is used to improve the communication process within the system and also to document, plan, analyze, design and integrate the methodology.

IDEF family has different techniques which are mentioned below. This study is limited to IDEF0 technique for explaining the functional methodology of the I/D determination stepwise procedure.

- IDEF0: for Function Modeling
- IDEF1: for Information Modeling
- IDEF1x: for Data Modeling
- IDEF3: for Process Modeling
- IDEF4: for Object – Oriented Design
- IDEF5: for Ontology Description Capture

The IDEF0 model diagram displayed in Figure 1 is based on a simple syntax (Talluri and Yoon 2000), wherein inputs are shown as arrows entering the left side of the activity box, while the outputs are shown as exiting arrows on the right side of the box. Controls are displayed as arrows entering the top of the box, and mechanisms are displayed as arrows entering from the bottom of the box. Inputs, controls, outputs and mechanisms (ICOMs) are all referred to as concepts.

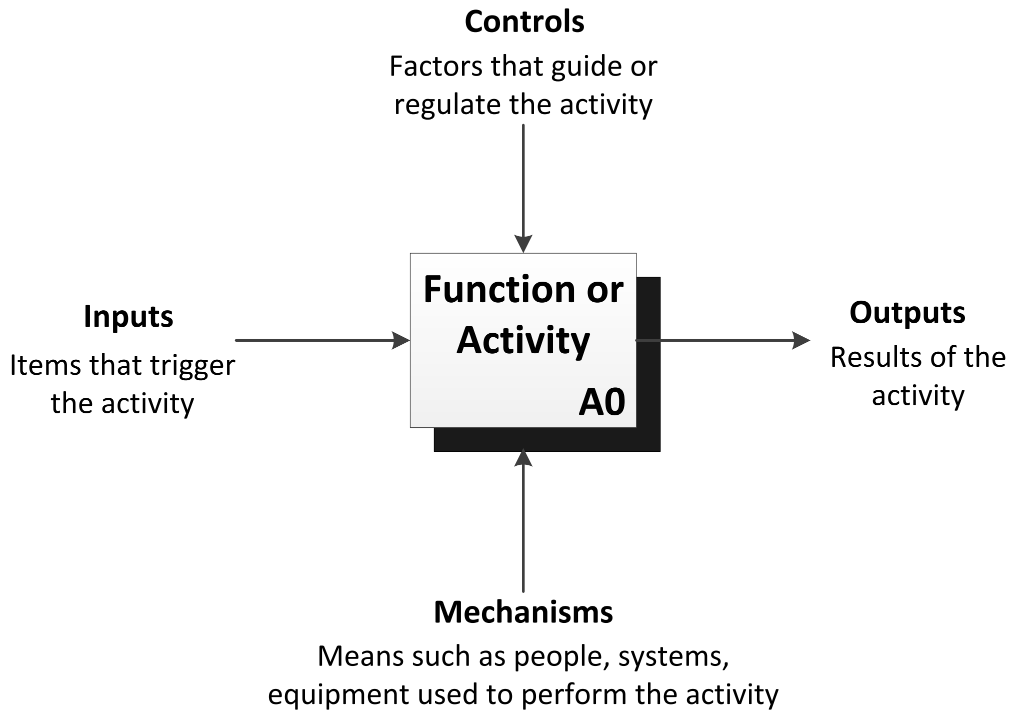


Figure 1. Basic IDEF0 Syntax

IDEF0 Modeling technique consists of several activities arranged in a top to bottom fashion. A simple hierarchical structure of an IDEF0 model is mentioned below in Figure 2. This top-level function is decomposed into sub-function parts and is further decomposed until all of the relevant detail of the whole function is adequately visible (Waltman and Presley 1993). This process is called creating a child diagram. Level of detail also goes on increasing as we go down in the structure.

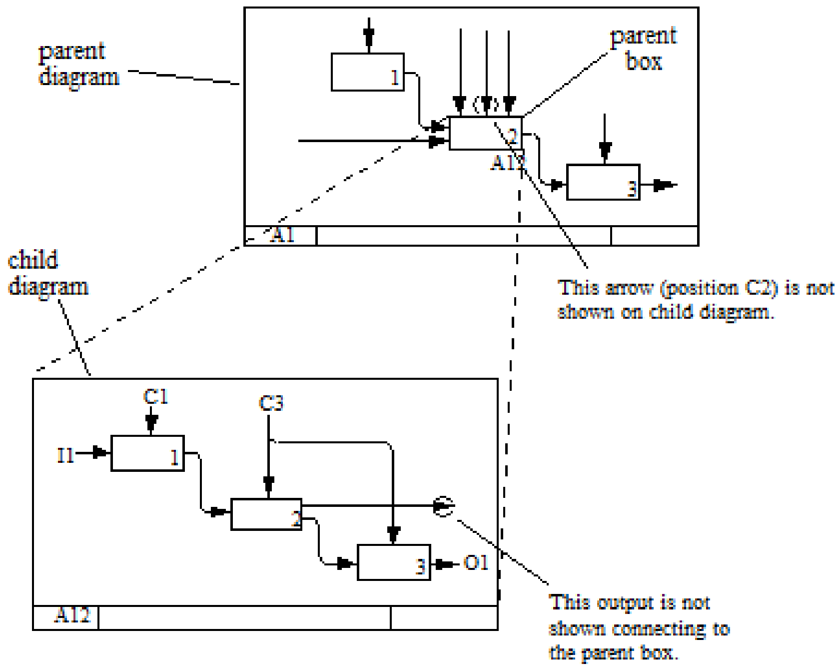


Figure 2. IDEF0 Model Decomposition Structure

2.3.2 CA4PRS Tool

CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) is a state-of-the art tool which has come into use because of its ability to analyze schedules, costs, and work zone traffic impacts. CA4PRS's schedule analysis estimates the duration of highway rehabilitation project in terms of total number of closures by considering the following critical factors that affect project duration: project scope (lane-mile to be rebuilt), construction strategies (e.g., concrete, asphalt concrete, milling, etc), cross-section designs, construction windows (e.g., nighttime, weekend, extended 24/7 operations), and contractor logistics and resource constraints (Lee and Ibbs, 2005).

CA4PRS played a pivotal role in this research in generating the baseline data for integration of schedule/time value savings/additional cost growth. Since the scheduling reliability and accuracy of CA4PRS was validated with numerous highway renewal projects, it was assumed that the program's use would provide reliable baseline data. It was used to estimate the number of closures the project would take to complete the project, reduction in road user costs by shortening construction time; and the number of closures (days) a contractor can reasonably eliminate under four given resource levels.

Figure 3 shows a screenshot of the input/output screen of the CA4PRS software which highlights project details, activity constraints, resource profile, schedule analysis, and work zone analysis. The details from any given project can be put into the software which runs the cost/schedule/traffic simulations.

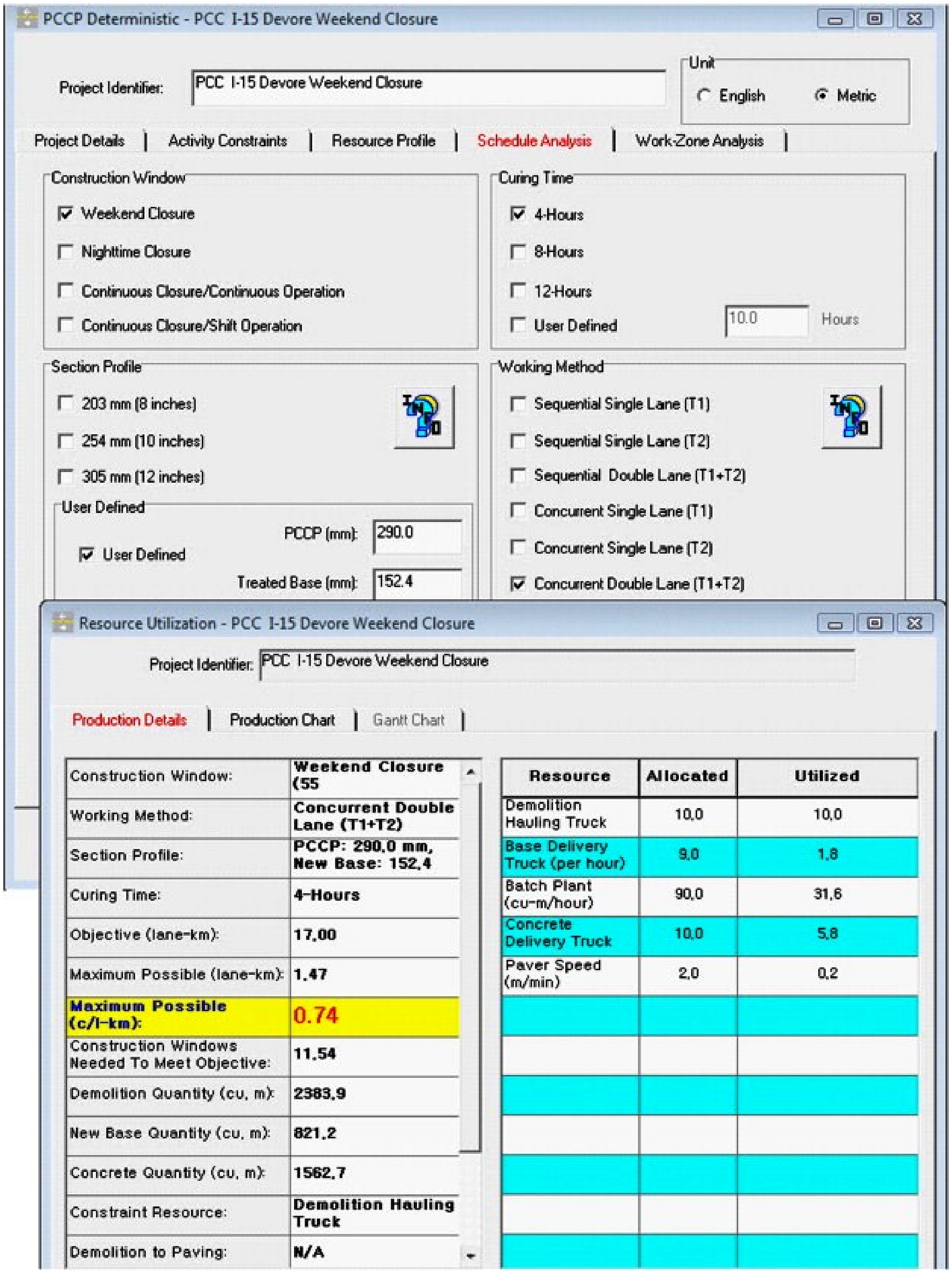


Figure 3. CA4PRS Input/Output Screenshot

2.4 Limitations

- Validation of the research results has been done on projects limited only to the state of California, due largely to the lack of accurate data outside the state of California.
- Validation of I/D upper bound using net present value concept has been done using hypothetical cases which involve/assume loan mortgage from the funding agencies.
- The research does not take into account escalating incentives, rather only linear incentives in which the same daily amount is charged irrespective of the number of days it took to complete the project early or late (Shr and Chen 2004).
- This study uses only signalized intersections to calculate the discounting factors to determine point based I/D lower bound.

2.5 Contributions of the Research

This project involves simulation-based systematic stochastic approaches to capturing schedule (baseline of I/D), CAC (I/D lower bound), and total time savings (I/D upper bound) concurrently by combining existing CA4PRS schedule and traffic simulations with an advanced stochastic analysis. This project provides STAs with the first view and systematic estimation method that they can use to determine the most economical and realistic I/D dollar amount for a given project between its additional cost to the contractor and benefit to the road users–an optimal value that allows the agency to stay within budget while effectively motivating contractors to complete projects ahead of schedule. The concepts of level of services along with adopting a net present value analysis technique enhance the model's capability in adjusting the CAC and total time savings realistically. Once successfully completed, the computer model with systematic analytical procedures would be applicable to a variety of transportation projects for quantifying optimal I/D dollar amounts that not only models the relationship of benefit-cost tradeoff, but also accounts for the contractor's additional commitments of time acceleration. Critically, it will also significantly reduce the agency's expenses in the time and effort required for determining I/D dollar amounts. Some of the contributions are summarized below:

1. Development of a novel framework that determines optimal I/D amount between CAC (Lower bound) and total savings (Upper bound) to road users and the agency.
2. Use of CA4PRS in arriving at the results. CA4PRS software was developed in a collaborative effort by University of California at Berkeley Pavement Research Center and FHWA, and has been shown to be reasonable in predicting optimum pavement construction production using actual construction projects and can be a tool to back-analyze historical I/D projects to determine their effectiveness and lessons learned where improvements can be made.
3. CAC is adjusted by applying the concept of Level of Service (LOS), thus better reflecting the CAC for expediting construction.
4. In the CAC estimate, regression models were developed for four generic types of pavement such as JPCP, CRCP, HMA and MACO. Therefore, the predictive regression models are applicable to all types of highway renewal projects.

5. Due to the budget constraints, STAs cannot apply the same I/D amounts equivalent to the estimated total savings (RUC + AC). However, a clear methodology has not been developed to discount I/D amount from the total savings. This study addresses this issue to capture more reasonable and realistic I/D amounts by adopting Net Present Value (NPV) analysis.
6. Therefore, the I/D amounts determined through the proposed framework mirror both CAC of acceleration (Cost) and total savings (Benefit), each of which is adjusted.
7. The research results and decision support model will help State Transportation Agencies (STAs) make better informed decisions regarding allocation of incentives for alternate contracting projects.
8. The SHAs will be in a better position to accurately predict realistic budgets when going for I/D contracting projects.

3 LITERATURE REVIEW

Time-based, cost-based and quality-based I/D are the three type of contracting strategies discussed till date which focus on early completion of work, reduction in project cost, and enhancing quality and safety of the project, respectively. Time-based I/D are considered to be comparatively easy and inexpensive to implement, and hence are the most popular out of the three in highway construction projects (Ellis and Pyeon 2005). FHWA (1998) described time-based I/D contracting strategy as "A contract provision that compensates the contractor a certain amount of money for each day identified critical work is completed ahead of schedule and assesses a deduction for each day the contractor overruns the I/D time". Time-based I/D provisions by virtue of completing the projects ahead of their assigned schedule result in substantial time and cost savings.

The determination of the appropriate dollar amount has been one of the most important issues in the use of I/D provisions (Arditi and Yasamis 1998; Gillespie 1998). For the determination of the I/D amount, FHWA (1998) clearly stated, "The dollar amount must be of sufficient benefit to the contractor to encourage his/her interest, stimulate innovative ideas, and increase the profitability of meeting tight schedules so as to be effective and accomplish the objectives of I/D provisions." It is also mentioned that the incentive payment should be sufficient to cover the contractor's cost for the extra work to produce the intended results.

3.1 Federal Highway Administration (FHWA 1998) Guidelines for Determining the I/D Amount:

1. A daily I/D amount is calculated on a project-by-project basis using established construction engineering inspection costs, state-related traffic control and maintenance costs, detour costs, and road user costs. Costs attributed to disruption of adjacent businesses should not be included in the daily I/D amount. Engineering judgment may be used to adjust the calculated daily amount downward to a final daily I/D amount. A daily I/D amount should provide a favorable benefit/cost ratio to the traveling public and be large enough to motivate the contractor.
2. Estimation of RUC may be done using acceptable state highway agency's policies and procedures.
3. Most recent information should be used for calculating Vehicle Operating Cost (VOC).
4. The daily incentive rate should never exceed the daily disincentive rate.
5. A maximum of 5% has been specified as the incentive cap with no recommendation on the maximum disincentive amount.

3.2 Evaluation of I/D Amount

Several research studies have been conducted in the past to evaluate the right I/D for critical civil transportation projects, but there is lot of variation across all the state DOTs. I/D dollar amount should include costs related to the safety of the users, monetary value of the time lost; cost of fuel wasted, and increased administration, maintenance and monitoring cost associated with the use of I/D contracting strategies (Christiansen 1987; Jaraiedi et al. 1995; Shr and Chen 2004). In general, the criteria in determining I/D dollar amount should reflect the cost of savings/delay to the public and the savings/extra administration cost to the SHAs (Christiansen 1987; Herbsman et al. 1995; Shr and Chen 2004). The contractors' additional cost for acceleration is project specific and generally increases on a daily basis, but the framework required to measure the exact cost is either not developed properly or varies across the state DOTs (Pyeon and Lee 2012).

3.3 I/D Amount Calculation Methods

In order to determine the optimum I/D amount and duration, the I/D amount paid by the agency and the contractor's actual cost for expediting the work should be identified. For many STAs, the incentive amount provided is usually equal to the amount the owners save in daily road user cost. Generally speaking, the contractor's daily cost for a project increases over time, but the exact daily cost is unknown and can vary from one project to another.

(Jaraiedi et al. 1995) introduced an algorithm that determines whether the I/D contract for a project is necessary or not. In this algorithm, the authors defined the contractor's extra costs to complete a project ahead of schedule as follows: "A is a fixed, one-time cost for marshaling extra crews and equipment to expedite the work and ordering of materials for early delivery; B is a variable cost per day of using the additional crews and equipment to expedite the project." If X is the number of days expedited, then, A + BX will be the total cost to the contractor for completing the project earlier. The authors recommended that the contracting agency examine the contractor's past experience with bidding in order to determine a range of values that could be used to represent both fixed and variable costs to the contractor.

The Alternative Contracting Draft User's Guide (Ellis et al. 2007) introduced two different methods for calculating daily I/D amount. In the linear method most commonly used in the United States, the contractor receives the same daily incentive amount regardless of the number of days completed early, and is charged the same way if the project is completed late. In the non-linear method, which escalates I/D that the failure-to-work provision applies to incentive, "the earlier a work is completed, the greater the daily amount paid to the contractor, or the later a project is completed, the more the daily amount is assessed against the contractor." The linear method was most frequently implemented in determining I/D amounts.

Recently, (Jiang et al. 2010) developed time-cost equations for various highway construction projects to estimate road user costs in highway work zones and evaluated the effect of road user costs on I/D values. Then they calculated the maximum incentive amounts and days with daily I/D amounts based on 20, 25, 30, 35, and 40 percent of the daily road user cost.

3.4 Factors Affecting the Level of Road User Cost (RUC)

Daily RUC is defined as “the estimated daily cost to the traveling public resulting from the construction work being performed” (Ibarra et al. 2002). RUC is used to determine appropriate I/D amount and is dependent on the following factors:

a. Location of the project
b. Percentage of truck and passenger car equivalent (PCE) factor
c. Width of the lanes
d. Vehicle operating cost (VOC)
e. Number of lanes opened to traffic
f. Additional travel time due to lane closures
g. Monetary value of time
h. Inflation (growth) rate
i. Traffic reduction rate
j. Favorable cost benefit ratio
k. Equal incentive and disincentive rates
l. Cap of maximum 5% on the incentives, no cap on disincentives

4 STEPWISE PROCEDURES TO ARRIVE AT OPTIMAL I/D*

Following section highlights the stepwise procedures aimed at determining optimal I/D dollar amounts:

Step 1 Estimate baseline schedules with CA4PRS: Perform CA4PRS simulations with four different resource usage levels on four different types of pavements.

Step 2 Develop predictive models that determine CAC (Initial lower bound of I/D): Calculated on the basis of resource usage levels using cost growth equation.

Step 3 Quantify savings in Road User Costs (Initial upper bound of I/D – I): RUC was quantified by evaluating the impact of construction work zone on travelling public using CA4PRS traffic simulation analysis.

Step 4 Quantify savings in Agency Costs (Initial upper bound of I/D – II): Agency cost savings were estimated using the schedule compression rates.

Step 5 Adjust the CAC from step 2 ("Adjusted" lower bound): Adjust the cost aspect with Level of Service (LOS).

Step 6 Adjust the total savings from step 3 – 4 ("Adjusted "upper bound): Adjust the benefit aspect using Net Present Value (NPV).

Step 7 Determine I/D between Adjusted CAC and total savings: Calculate point based estimates of Daily, Closure and Maximum I/D based on the comparison of CAC using LOS and total savings using NPV.

*Part of the data in this chapter is reprinted with permission from "*A New Decision-support Model for Innovative Contracting Strategies Through a Quantitative Analysis on Aspects of Project Performance*" by Choi, K. ProQuest, Copyright (2008) by Choi, K.
*Part of the data in this chapter is reprinted with permission from "Decision Support Model for Incentives/Disincentives Time Cost Tradeoff." by Choi, K., and Kwak, Y. H. (2012). *Automation in Construction*, 21, 219-228, Copyright (2012) by Choi, K.

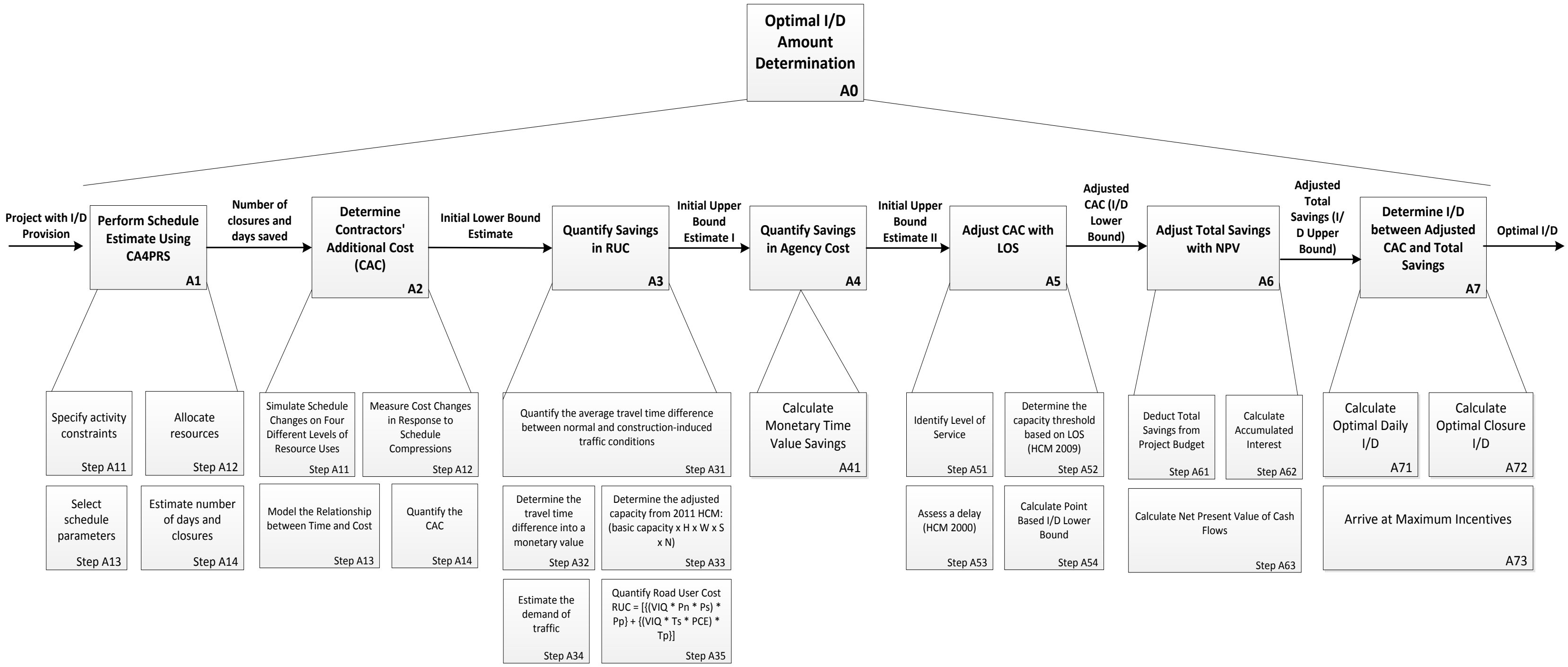


Figure 4. Framework for Determining Optimal I/D

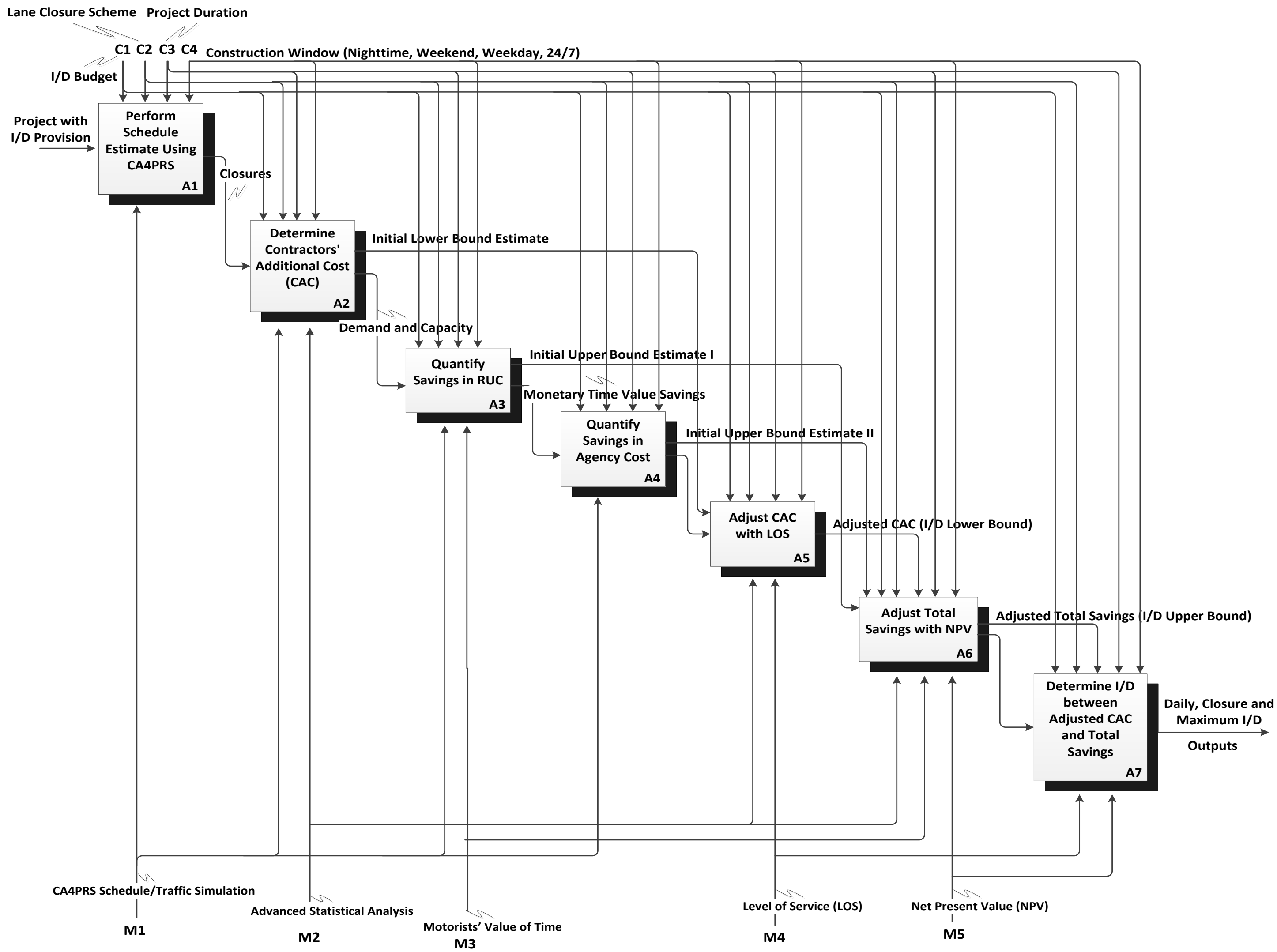


Figure 5. Optimal I/D Amount Determination Using IDEF0 Flowchart

4.1 STEP 1: Schedule Estimate Using CA4PRS

Figure 4 highlights the stepwise procedures aimed at arriving optimal I/D amount using the concept of IDEF0 flowchart. Figure 5 on the next page is again a detailed explanation of the various steps of the IDEF0 process. CA4PRS can be used to quantify the number of closures/working days by which the project can be shortened by using I/D strategies. Contractors often are able to complete the projects ahead of schedule, thereby receiving incentives without putting any additional effort. Therefore, it is very important to arrive at the most realistic I/D amount. Figure 6 highlights the important factors affecting schedule estimate.

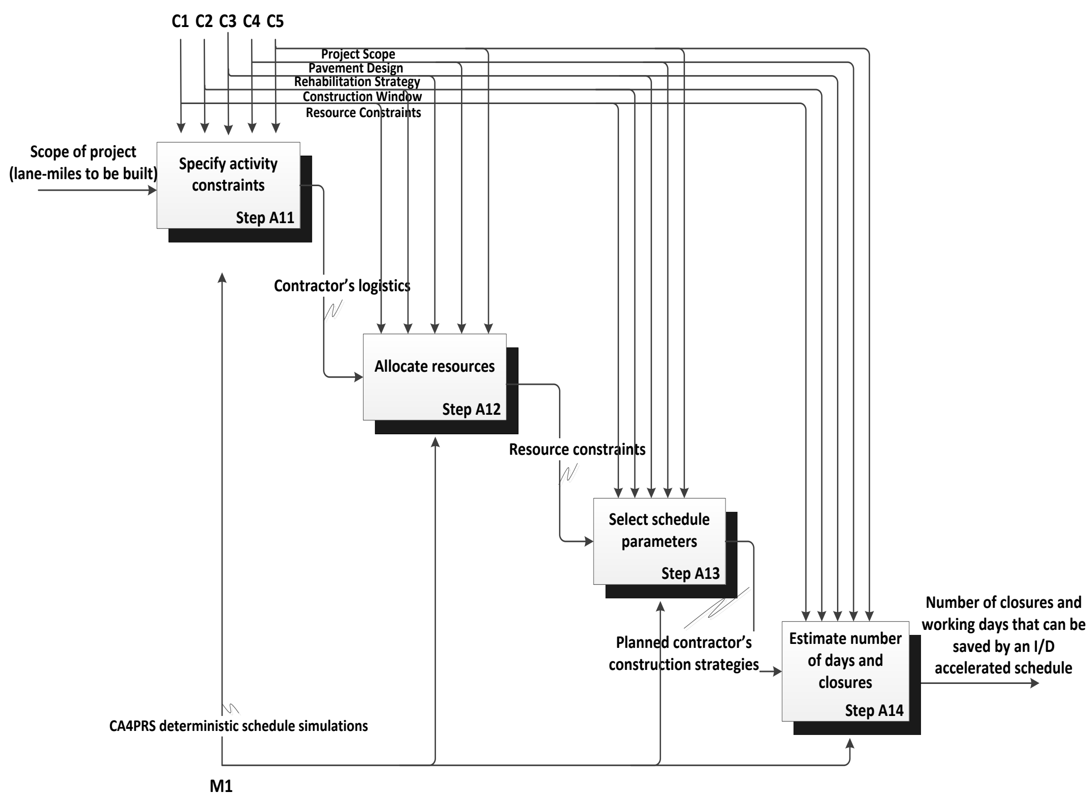


Figure 6. IDEF0 Flowchart for Estimate Baseline Schedules Using CA4PRS

4.1.1 Baseline Schedule

It has been reported that CA4PRS provides accurate schedule estimates of highway renewal projects (Lee et al., 2008), therefore the program was used to develop a database of schedule estimate lookup tables by considering five critical factors as specified in figure 7, that significantly affect project schedule (Tables 1−5):

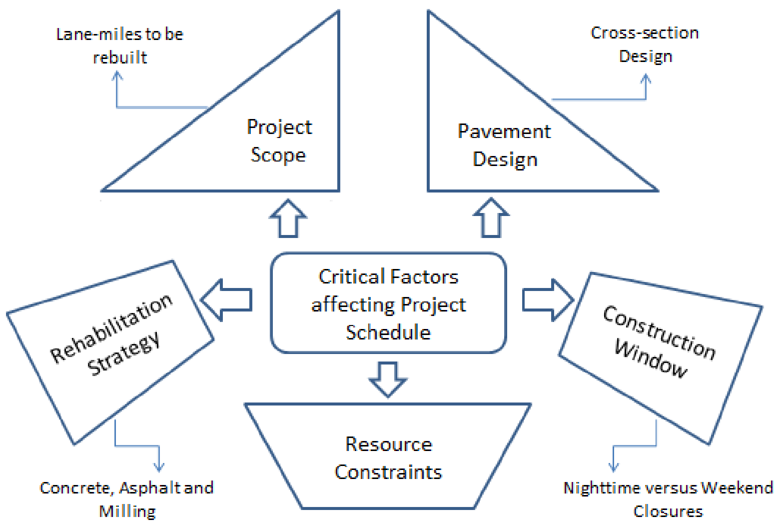


Figure 7. Factors Affecting Project Schedule

The schedule module incorporates the database to produce reliable schedule estimates including the number of closures and working days that can be saved by comparing the effort required to use a conventional schedule strategy and an incentive schedule strategy.

The estimated difference between the number of closures necessary to complete a project by using a conventional schedule and an incentive schedule determines the maximum probable number of closures and working days that can be saved by using an incentive schedule. This schedule estimate is essential in that the daily I/D and maximum incentive amounts are determined as a function of the time the project can save.

4.1.2 Modeling Using CA4PRS

1. Identifies the mobilization and demobilization hours depending on the requirements of the project. Lag time is also assigned in this stage which depends on whether the project is accompanied by sequential or concurrent paving strategy.
2. Resource allocation is dependent on five major factors namely, demolition hauling truck, base delivery truck, batch plant, concrete delivery truck and pavers, all of which are project specific.
3. Schedule for an I/D project is an accelerated one that commits additional resources, namely, 15% more for a strategy that uses concrete and 20% more for strategies that use asphalt concrete and milling.
4. The estimated number of closures on the 55-hour weekend window was converted into working days because current Caltrans practice calls for use of working days rather than calendar days when determining I/D project completion times.
5. The number of weekend closures was multiplied by 2.29 for the conversion to working days.
6. The maximum probable number of days that can be saved was then calculated using the difference in the number of days required to complete the project with a conventional schedule and with an I/D schedule (Tables 1−5).

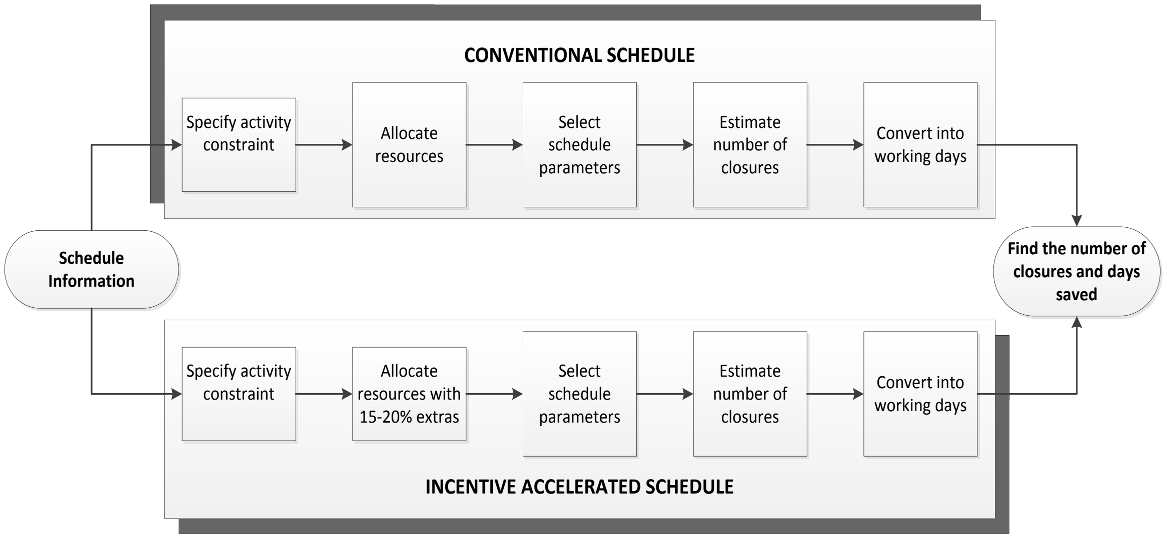


Figure 8. Schedule Module Using CA4PRS Conventional vs. Incentive

Figure 8 highlights the basic concept in calculating the number of days and closures saved by comparing a conventional schedule with an incentive accelerated schedule.

4.1.3 CA4PRS Schedule Estimate Strategies

The following tables (1-5) highlight the maximum probable number of days that can be saved to complete the project using I/D contracting strategies as compared to a conventional one.

Table 1. CA4PRS Schedule Estimate with Nighttime Construction

Scope (lane-mile)	Ordinary Schedule 8-hrs window		Incentive Schedule 8-hrs window		Number of Closures Saved	
	8''	12'' with 6'' base	8''	12'' with 6'' base	8''	12'' with 6'' base
	A	B	C	D	E	F
1	19	28	17	24	2	4
2	38	56	33	49	5	7
3	57	83	50	73	7	10
4	76	111	66	97	10	14
5	94	139	82	121	12	18
6	113	166	99	145	14	21
7	132	194	115	169	17	25
8	151	222	131	193	20	29
9	170	249	148	217	22	32
10	188	277	164	241	24	36
11	207	305	180	265	27	40
12	226	332	197	289	29	43
13	245	360	213	313	32	47
14	264	388	229	337	35	51
15	282	415	246	361	36	54
16	301	443	262	385	39	58
17	320	470	278	409	42	61
18	339	498	295	433	44	65
19	358	526	311	457	47	69
20	376	553	327	481	49	72

(E) Column = (A) Column – (C) Column
(F) Column = (B) Column – (D) Column

Table 2. CA4PRS Schedule Estimate with 55-hour Weekend Construction

Scope (lane-mi)	Ordinary Schedule 55-hrs window				Incentive Schedule 55-hrs window				Number of Closures and Days Saved			
	8''		12'' with 6'' base		8''		12'' with 6'' base		8''		12'' with 6'' base	
	Closures A	Days B	Closures C	Days D	Closures E	Days F	Closures G	Days H	Closures I	Days J	Closures K	Days L
1	0.8	2	1.6	4	0.7	2	1.4	3	0.1	0	0.2	1
2	1.5	3	3.1	7	1.3	3	2.7	6	0.2	0	0.4	1
3	2.3	5	4.7	11	2	5	4.1	9	0.3	0	0.6	2
4	3	7	6.3	14	2.6	6	5.4	12	0.4	1	0.9	2
5	3.8	9	7.8	18	3.3	8	6.8	16	0.5	1	1	2
6	4.6	11	9.4	22	4	9	8.2	19	0.6	2	1.2	3
7	5.3	12	10.9	25	4.6	11	9.5	22	0.7	1	1.4	3
8	6.1	14	12.5	29	5.3	12	10.9	25	0.8	2	1.6	4
9	6.8	16	14.1	32	5.9	14	12.2	28	0.9	2	1.9	4
10	7.6	17	15.6	36	6.6	15	13.6	31	1	2	2	5
11	8.4	19	17.2	39	7.3	17	15	34	1.1	2	2.2	5
12	9.1	21	18.8	43	7.9	18	16.3	37	1.2	3	2.5	6
13	9.9	23	20.3	47	8.6	20	17.7	41	1.3	3	2.6	6
14	10.6	24	21.9	50	9.2	21	19	44	1.4	3	2.9	6
15	11.4	26	23.4	54	9.9	23	20.4	47	1.5	3	3	7
16	12.2	28	25	57	10.6	24	21.7	50	1.6	4	3.3	7
17	12.9	30	26.6	61	11.2	26	23.1	53	1.7	4	3.5	8
18	13.7	31	28.1	64	11.9	27	24.5	56	1.8	4	3.6	8
19	14.4	33	29.7	68	12.6	29	25.8	59	1.8	4	3.9	9
20	15.2	35	31.3	72	13.2	30	27.2	62	2	5	4.1	10

1. (I) Column = (A) Column – (E) Column
2. (J) Column = (B) Column – (F) Column
3. (K) Column = (C) Column – (G) Column
4. (L) Column = (D) Column – (H) Column

Table 3. CA4PRS Schedule Estimate with 72-hour Weekday Construction

Scope (lane-mi)	Ordinary Schedule 55-hrs window				Incentive Schedule 55-hrs window				Number of Closures and Days Saved			
	8''		12'' with 6'' base		8''		12'' with 6'' base		8''		12'' with 6'' base	
	Closures A	Days B	Closures C	Days D	Closures E	Days F	Closures G	Days H	Closures I	Days J	Closures K	Days L
1	0.3	1	0.7	2	0.3	1	0.6	2	0	0	0.1	0
2	0.7	2	1.4	4	0.7	2	1.2	4	0	0	0.2	0
3	1	3	2.2	7	1	3	1.8	5	0	0	0.4	2
4	1.3	4	2.9	9	1.3	4	2.4	7	0	0	0.5	2
5	1.6	5	3.6	11	1.6	5	3	9	0	0	0.6	2
6	2	6	4.3	13	2	6	3.6	11	0	0	0.7	2
7	2.3	7	5.1	15	2.3	7	4.2	13	0	0	0.9	2
8	2.6	8	5.8	17	2.6	8	4.8	14	0	0	1	3
9	3	9	6.5	20	2.9	9	5.4	16	0.1	0	1.1	4
10	3.3	10	7.2	22	3.3	10	6	18	0	0	1.2	4
11	3.6	11	7.9	24	3.6	11	6.6	20	0	0	1.3	4
12	3.9	12	8.7	26	3.9	12	7.2	22	0	0	1.5	4
13	4.3	13	9.4	28	4.3	13	7.8	23	0	0	1.6	5
14	4.6	14	10.1	30	4.6	14	8.4	25	0	0	1.7	5
15	4.9	15	10.8	32	4.9	15	9	27	0	0	1.8	5
16	5.3	16	11.5	35	5.2	16	9.6	29	0.1	0	1.9	6
17	5.6	17	12.2	37	5.6	17	10.2	31	0	0	2	6
18	5.9	18	13	39	5.9	18	10.8	32	0	0	2.2	7
19	6.2	19	13.7	41	6.2	19	11.4	34	0	0	2.3	7
20	6.6	20	14.4	43	6.5	20	12	36	0.1	0	2.4	7

Table 4. CA4PRS Schedule Estimate of Asphalt Concrete: Nighttime vs. Weekend

Scope (lane-mi)	Ordinary Schedule				Incentive Schedule				Number of Closures and Days Saved			
	Nighttime		55-hours		Nighttime		55-hours		Nighttime		55-hours	
	Closures A	Days B	Closures C	Days D	Closures E	Days F	Closures G	Days H	Closures I	Days J	Closures K	Days L
5	71	71	1.5	3	60	60	1.3	3	11	11	0.2	0
10	142	142	3.1	7	119	119	2.6	6	23	23	0.5	1
15	213	213	4.6	11	178	178	3.8	9	35	35	0.8	2
20	284	284	6.1	14	237	237	5.1	12	47	47	1	2
25	355	355	7.7	18	296	296	6.4	15	59	59	1.3	3
30	426	426	9.2	21	355	355	7.7	18	71	71	1.5	3
35	497	497	10.7	25	415	415	8.9	20	82	82	1.8	5
40	568	568	12.3	28	473	473	10.2	23	95	95	2.1	5
45	639	639	13.8	32	533	533	11.5	26	106	106	2.3	6
50	710	710	15.3	35	592	592	12.8	29	118	118	2.5	6
55	781	781	16.8	39	651	651	14	32	130	130	2.8	7
60	852	852	18.4	42	710	710	15.3	35	142	142	3.1	7
65	923	923	19.9	46	770	770	16.6	38	153	153	3.3	8
70	994	994	21.4	49	829	829	17.9	41	165	165	3.5	8
75	1065	1065	24.5	56	888	888	19.1	44	177	177	5.4	12
80	1136	1136	25	57	947	947	20.4	47	189	189	4.6	10

Table 5. CA4PRS Schedule Estimate of MACO: Nighttime vs. Weekend

Scope (lane-mi)	Ordinary Schedule				Incentive Schedule				Number of Closures and Days Saved			
	Nighttime		55-hours		Nighttime		55-hours		Nighttime		55-hours	
	Closures A	Days B	Closures C	Days D	Closures E	Days F	Closures G	Days H	Closures I	Days J	Closures K	Days L
5	18	18	2.3	5	16	16	2.1	5	2	2	0.2	0
10	35	35	5	11	32	32	4.2	10	3	3	0.8	1
15	52	52	6.9	16	48	48	6.3	14	4	4	0.6	2
20	70	70	9.2	21	64	64	8.4	19	6	6	0.8	2
25	87	87	11.5	26	80	80	10.4	24	7	7	1.1	2
30	104	104	13.8	32	96	96	12.5	29	8	8	1.3	3
35	121	121	16.1	37	110	110	14.6	33	11	11	1.5	4
40	139	139	18.4	42	127	127	16.7	38	12	12	1.7	4
45	156	156	20.7	47	143	143	18.8	43	13	13	1.9	4
50	173	173	22.9	52	159	159	20.9	48	14	14	2	4
55	190	190	25.2	58	175	175	23	53	15	15	2.2	5
60	208	208	27.5	63	191	191	25.1	58	17	17	2.4	5
65	225	225	29.8	68	207	207	27.1	62	18	18	2.7	6
70	242	242	32.1	74	222	222	29.2	67	20	20	2.9	7
75	260	260	34.4	79	238	238	31.3	72	22	22	3.1	7
80	277	277	36.7	84	254	254	33.4	77	23	23	3.3	7

4.2 STEP 2: Contractors' Additional Cost (CAC) for Determining Initial Lower Bound of I/D

The IDEF0 flowchart showed in figure 9 highlights the procedure for determining initial lower bound of I/D using the concept of time-cost tradeoff.

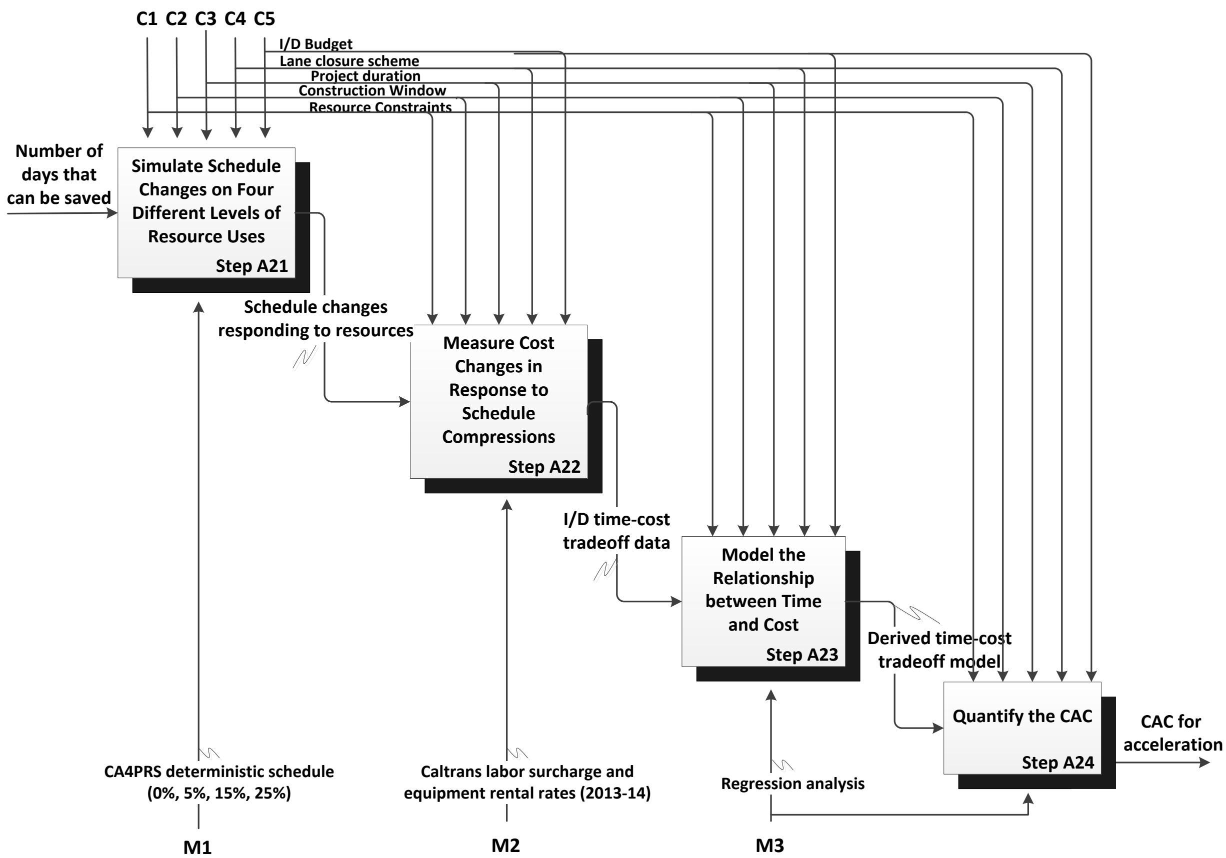


Figure 9. Flowchart for Estimating Initial Lower Bound of I/D

4.2.1 Time-Cost Tradeoff

It was observed that a tradeoff exists between the time required to complete the projects in time and the additional cost on the part of the contractors' to complete the project ahead of schedule. A new approach was undertaken to determine the optimal I/D amount that will motivate contractors to pursue accelerated construction. Using CA4PRS, simulation-based contractors' time-cost tradeoff data were created based on four different resource usage levels. A linear regression analysis with the data was conducted to predict the contractors' additional cost growth rate and how it interacts with the agency's specified schedule goal.

Figure 10 shows the time-cost trade-off. To complete the project earlier by a duration ΔT (i.e. to shorten the project from t_0 to t_1), a contractor would need to incorporate extra resources which would increase the cost by ΔC (i.e. the CAC would increase from C_0 to C_1). This time-cost tradeoff helps to ascertain the additional resources to be employed by the contractors' to complete the project ahead of the specified schedule. As mentioned earlier truck, paver, milling machine and batch plant are the four major sources of increased cost growth. Depending on the timeline assigned to complete the projects, the contractors' manipulate these resources to come up with the desired results.

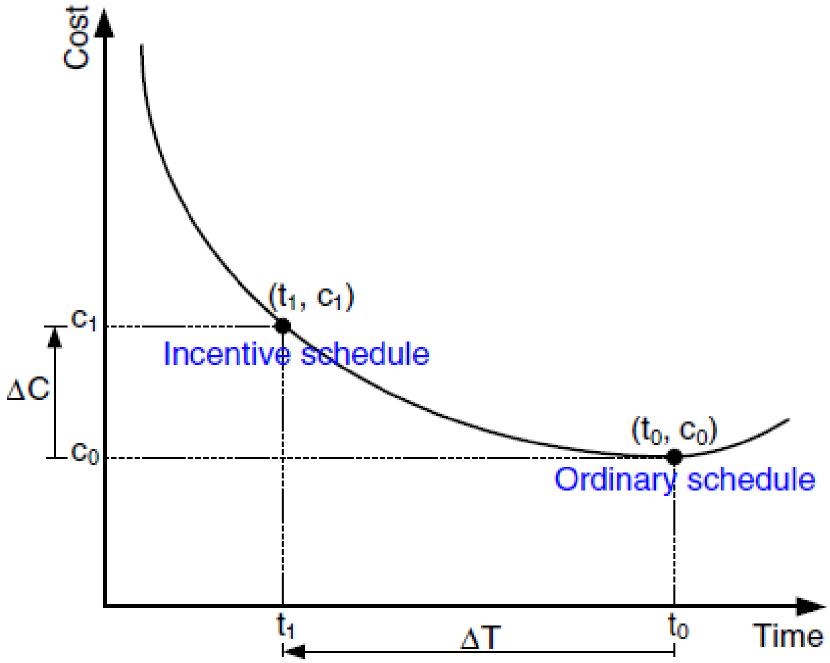


Figure 10. Time-Cost Tradeoff Curve

From the figure, it is observed that the time-cost trade-off is of the quadratic form and can be represented using a second order polynomial equation.

$Cost = \beta_0 + \beta_1 \, (Time) + \beta_2 \, (Time)^2$

4.2.2 Equation Derivation Using Time-Cost Tradeoff

From the results obtained by the regression analysis, the coefficients β_0, β_1, *and* β_2 can be determined, and a time function can be generated on the basis of these coefficients.

$f = \beta_0 + \beta_1 t + \beta_2 t^2$

Since the CAC increase is expressed as a function of shortening time by ΔT, the following relationship can be derived from Fig 7.

$\text{CAC}(\Delta T) = f(t_1) - f(t_0) = f(t_1) - f(t_1 + \Delta T)$, where, $t_o = t_1 + \Delta T$

By combining the above two mentioned equations, we derive the final equation for CAC,

$\Delta C = -\Delta T\,(2\beta_2 t_1 + \beta_1 + \beta_2 \Delta T)$

The negative sign indicates that cost and time have an inverse relationship. This is very obvious as for completing the project earlier by a duration ΔT, the contractors' will need to employed additional resources which will increase the cost growth by ΔC.

The projects on which these strategies were utilized used I/D contracting strategies in order to complete the projects ahead of schedule by employing additional resources. The schedule simulations were run using four different resource usage levels, ordinary, 5% increase, 15% increase and 25% increase. 10 hour nighttime closures, 55 hour weekend closures, and 24/7 extended closures were identified as the major construction work zone analysis in the schedule simulations. All these closures allow long-life pavements which last in excess of 30 years, thereby complying with the Caltrans Long Lasting Pavement Rehabilitation Strategies (LLPRS).

4.2.3 Equation to Calculate Contractors' Additional Cost

Caltrans Labor Surcharge and Equipment Rental Rates 2013-14 manual was used to calculate the additional cost growth by taking into account the unit price information of all the resources used. The unit prices of all the major resources on the basis of the latest manual are $88.70 with overtime rate of 0.86 (Truck), $139.67 with overtime rate of 0.88 (Paver), \$413.38 with overtime rate of 0.90 (Milling Machine), and \$688 with overtime rate of 0.59 (Batch Plant).

Equation used to calculate the cost growth is:

CAC = unit price (\$ / h) × number of additional resources × labor surcharge rate × working hours per day × days needed to complete the project × overtime rate × number of shifts × overhead cost (15%)

Unit price as mentioned above includes the labor costs, and the labor surcharge rate includes all the miscellaneous factors such as payroll data, fringe benefits, and taxes. The surcharge rate for the year 2013-14 is 12% for regular time and 11% for overtime, as per the Caltrans manual.

4.2.4 CA4PRS Schedule Analysis on Four Pavements Strategies

As specified in the earlier section, CA4PRS was used to generate the data for this research study. The four main strategies (highway profiles) on which the schedule simulations were run are as follows:

1. Jointed Portland Concrete Pavement (JPCP)

This is a very common type of rigid pavement, which is very useful in controlling the cracks in the pavements by connecting all the individual slabs along the pavement by contraction joints. These pavements primarily use concrete as their binding material based on the assumption that cracks occur only at the joints (Khanum et al. 2006). JPCP does not use any steel reinforcement except for dowels and tie-bars at the transverse and longitudinal joints (Khanum et al. 2006). The thickness of these pavements range anywhere from 7 inches to 13 inches (Khanum et al. 2006). Most of the highway pavements in the US are made of JPCP.

2. Continuously Reinforced Concrete Pavement (CRCP)

Contrary to JPCP, CRCP does not use steel for transverse and longitudinal joints but reinforcement for controlling cracks (Muga et al. 2009). It is specifically used in excessively deteriorated highway pavements and costs lot more than the CRCP type (Muga et al. 2009). Thickness of CRCP is almost in the same range as that of JPCP

3. Hot Mix Asphalt (HMA)

This is another type of paving material in which the surface mixture is prepared by heating the aggregate in excess of 300 ^{0}F. Advantage of using asphalt in place of concrete is that it can be easily installed in much less time, and at the same time provides same durability, strength and life at almost the same cost (Lee et al. 2008). In HMA, the compaction activity is performed as soon as the pavement is laid, otherwise the pavement might cool down resulting in improper settling of the surface. Thickness for this type of pavement ranges from 6 inches to 10 inches (Lee et al. 2008).

4. Milling and Asphalt Concrete Overlay (MACO)

In this type of strategy, the old deteriorated pavement is removed by milling and is replaced with new asphalt concrete layers. MACO is specifically useful for pavements where there is minimum need to disrupt the existing subgrade profile, rather top layers of the pavement are laid to prevent shoving, ruts, and cross-sectional imperfections (Labi et al. 2005). Thickness of MACO strategies is generally in the range of 3 inches to 6.5 inches (Labi et al. 2005).

4.2.5 Contractors Additional Cost (CAC) of Accelerated Construction

CAC of acceleration for four different types of pavements was calculated by measuring reduction in project time vs. cost growth (Tables 6 – 13).

Jointed Plain Concrete Pavement (JPCP) strategy is based on I-15 Devore, San Bernardino, Caltrans District 8 Demonstration Project (9-h Nighttime Closure). The scope of the project is to rebuild 17 lane-kilometer of badly deteriorated highway using fast setting hydraulic cement concrete (4-hour curing time) and one single lane reconstruction.

Continuously Reinforced Concrete Pavement (CRCP) strategy is based on Stockton, SJ County, CA, long-life CRCP I-5 Stockton (District 10) Reconstruction Project. The scope of the project is to rebuild 33.8 lane-kilometers of badly deteriorated highway by adopting two lanes closure and two lanes open, continuous lane closure and shift (daytime) construction.

Hot Mix Asphalt (HMA) strategy is based on I-710 Long Beach, CA, Caltrans AC (CSOL) Long-Life Rehabilitation Demonstration Project. The scope of the project is to rebuild 21 lane-kilometers of badly deteriorated highway by adopting 3 lanes in each direction including shoulders on both sides, and about 1.2 km stretch per weekend.

Milling and Asphalt Concrete Overlay (MACO) strategy is based on US-101 San Jose, Santa Clara County, CA, Milling and AC Overlay – Nighttime Closures (8-hour Nighttime). The scope of the project is to rebuild 88.5 lane-kilometers of badly deteriorated highway by adopting 4-5 lanes in each direction, South Bound 7 miles and North Bound 6 miles.

Table 6. CA4PRS Schedule Estimate vs. Additional Resource Usage for JPCP

Strategies	Cross-section profile	Construction window	Schedule estimate vs. additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
JPCP	8 in.	Nighttime	143.45	143.45	136.56	136.56	125.96	125.96	118.18	118.18
		Weekend	10.14	23.22	9.66	22.12	8.91	20.40	8.36	19.14
		Extended	3.85	30.80	3.50	28.00	3.21	25.68	2.96	23.68
	10 in.	Nighttime	210.00	210.00	199.28	199.28	182.78	182.78	170.68	170.68
		Weekend	18.71	42.85	17.76	40.67	16.29	37.30	15.21	34.83
		Extended	4.74	37.92	4.31	34.48	3.95	31.60	3.86	30.88
	12 in. with 6 in. ACB	Nighttime	229.77	229.77	218.10	218.10	200.14	200.14	186.97	186.97
		Weekend	20.47	46.88	19.43	44.49	17.83	40.83	16.66	38.15
		Extended	5.41	43.28	4.92	39.36	4.51	36.08	4.21	33.68

Table 7. Cost Growth by Virtue of Using Additional Resources for JPCP

Strategies	Cross-section profile	Construction window	Time-cost tradeoff vs. additional resource usage					
			5%		15%		25%	
			Schedule Compression	Cost Growth	Schedule Compression	Cost Growth	Schedule Compression	Cost Growth
JPCP	8 in.	Nighttime	4.80	0.40	12.19	1.21	17.62	2.01
		Weekend	4.73	0.63	12.13	1.07	17.55	1.52
		Extended	9.09	0.68	16.62	1.37	23.12	1.61
	10 in.	Nighttime	5.10	0.42	12.96	1.22	18.72	2.01
		Weekend	5.08	0.59	12.93	1.23	18.71	1.51
		Extended	9.07	0.71	16.67	1.47	18.57	1.72
	12 in. with 6 in. ACB	Nighttime	5.07	0.43	12.90	1.24	18.63	2.00
		Weekend	5.08	0.56	12.89	1.38	18.61	1.49
		Extended	9.06	0.74	16.64	1.56	22.18	1.82

Table 8. CA4PRS Schedule Estimate vs. Additional Resource Usage for CRCP

Strategies	Cross-section profile	Construction window	Schedule estimate vs. additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
CRCP	8 in.	Nighttime	717.55	717.55	704.68	704.68	682.28	682.28	660.19	660.19
		Weekend	20.06	45.94	19.17	43.90	17.57	40.24	17.57	40.24
		Extended	12.53	100.24	11.95	95.60	11.29	90.32	11.26	90.08
	10 in.	Nighttime	1125.34	1125.34	1109.30	1109.30	1081.41	1081.41	1057.98	1057.98
		Weekend	41.66	95.40	39.67	90.84	36.22	82.94	34.90	79.92
		Extended	23.48	187.84	22.36	178.88	20.42	163.36	19.01	152.08
	13 in. with 3 in. ACB	Nighttime	1158.98	1158.98	1138.15	1138.15	1101.93	1101.93	1071.46	1071.46
		Weekend	45.26	103.65	43.24	99.02	41.66	95.40	39.67	90.84
		Extended	24.71	197.68	23.77	190.16	23.48	187.84	22.36	178.88

Table 9. Cost Growth by Virtue of Using Additional Resources for CRCP

Strategies	Cross-section profile	Construction window	5% Schedule Compression	5% Cost Growth	15% Schedule Compression	15% Cost Growth	25% Schedule Compression	25% Cost Growth
CRCP	8 in.	Nighttime	1.79	0.16	4.92	0.48	7.99	1.11
		Weekend	4.44	0.41	12.41	0.16	12.41	2.58
		Extended	4.63	0.33	9.90	1.13	10.14	1.85
	10 in.	Nighttime	1.43	1.25	3.90	0.38	5.99	2.76
		Weekend	4.78	0.44	13.06	0.14	16.23	3.38
		Extended	4.77	0.34	13.03	1.49	19.04	3.67
	13 in. with 3 in. ACB	Nighttime	1.80	0.45	4.92	0.57	7.55	2.89
		Weekend	4.46	0.67	7.95	0.45	12.35	3.06
		Extended	3.80	0.89	4.98	1.56	9.51	4.13

Table 10. CA4PRS Schedule Estimate vs. Additional Resource Usage for HMA

Strategies	Cross-section profile	Construction window	Schedule estimate vs. additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
HMA (Simultaneous Paving)	8 in.	Nighttime	63.32	63.32	60.30	60.30	55.06	55.06	50.66	50.66
		Weekend	5.65	12.94	5.39	12.34	5.09	11.66	5.08	11.63
		Extended	1.06	7.42	1.01	7.07	0.95	6.65	0.95	6.65
	10 in.	Nighttime	80.12	80.12	76.45	76.45	69.23	69.23	63.78	63.78
		Weekend	7.09	16.24	6.76	15.48	6.38	14.61	6.37	14.59
		Extended	1.31	9.17	1.25	8.75	1.18	8.26	1.18	8.26
HMA (Pre-paving)	8 in.	Nighttime	41.92	41.92	38.94	38.94	35.65	35.65	34.63	34.63
		Weekend	3.76	8.61	3.56	8.15	3.25	7.44	3.14	7.19
		Extended	0.76	5.32	0.72	5.04	0.66	4.62	0.63	4.41
	10 in.	Nighttime	51.78	51.78	49.15	49.15	44.87	44.87	43.38	43.38
		Weekend	4.64	10.63	4.42	10.12	4.05	9.27	3.92	8.98
		Extended	0.93	6.51	0.89	6.23	0.81	5.67	0.78	5.46

Table 11. Cost Growth by Virtue of Using Additional Resources for HMA

Strategies	Cross-section profile	Construction window	Time-cost tradeoff vs. additional resource usage					
			5%		15%		25%	
			Schedule Compression	Cost Growth	Schedule Compression	Cost Growth	Schedule Compression	Cost Growth
HMA (Simultaneous Paving)	8 in.	Nighttime	4.78	0.42	13.04	1.27	15.22	2.12
		Weekend	4.60	0.42	9.91	1.27	10.09	2.10
		Extended	4.72	0.34	10.38	1.19	10.38	1.89
	10 in.	Nighttime	4.58	4.00	13.59	1.32	20.39	2.84
		Weekend	4.65	0.42	10.01	1.28	10.16	2.11
		Extended	4.58	0.33	9.92	1.14	9.92	1.81
HMA (Pre-paving)	8 in.	Nighttime	7.11	0.62	14.96	1.46	17.39	2.43
		Weekend	5.32	0.49	13.56	1.74	16.49	3.43
		Extended	5.26	0.38	13.16	1.51	17.11	3.12
	10 in.	Nighttime	5.08	4.44	13.34	1.29	16.22	2.26
		Weekend	4.74	0.49	12.72	1.63	15.52	3.22
		Extended	4.30	0.31	12.90	1.48	16.13	2.94

Table 12. CA4PRS Schedule Estimate vs. Additional Resource Usage for MACO

Strategies	Cross-section profile	Construction window	Schedule estimate vs. additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
MACO (Simultaneous Paving)	4 in.	Nighttime	232.17	232.17	227.96	227.96	219.58	219.58	213.65	213.65
		Weekend	25.84	11.28	25.36	58.07	24.41	55.90	23.69	54.25
		Extended	19.55	58.65	19.19	57.57	18.46	55.38	17.92	53.76
	6 in	Nighttime	359.48	359.48	353.21	353.21	340.78	340.78	330.53	330.53
		Weekend	40.00	91.60	39.09	89.52	37.82	86.61	36.75	84.16
		Extended	30.26	90.78	29.56	88.68	28.60	85.80	27.79	83.37
MACO (Pre-paving)	4 in.	Nighttime	126.24	126.24	120.25	120.25	109.82	109.82	101.06	101.06
		Weekend	17.92	41.04	17.07	39.09	15.67	35.88	14.77	33.82
		Extended	13.16	39.48	12.53	37.59	11.45	34.35	10.80	32.40
	6 in	Nighttime	235.54	235.54	230.49	230.49	223.04	223.04	216.15	216.15
		Weekend	27.50	62.98	26.87	61.53	25.99	59.52	25.26	57.85
		Extended	20.84	62.52	20.35	61.05	19.69	59.07	19.13	57.39

Table 13. Cost Growth by Virtue of Using Additional Resources for MACO

Strategies	Cross-section profile	Construction window	Time-cost tradeoff vs. additional resource usage					
			5%		15%		25%	
			Schedule Compression	Cost Growth	Schedule Compression	Cost Growth	Schedule Compression	Cost Growth
MACO (Simultaneous Paving)	4 in.	Nighttime	1.81	0.79	5.42	2.61	7.98	3.35
		Weekend	1.86	0.96	5.54	3.23	8.32	3.87
		Extended	1.84	0.93	5.58	2.99	8.34	3.99
	6 in.	Nighttime	1.74	0.77	5.20	2.51	8.05	3.65
		Weekend	2.28	1.18	5.45	3.18	8.12	3.89
		Extended	2.31	1.71	5.49	2.94	8.16	4.13
MACO (Pre-paving)	4 in.	Nighttime	2.14	0.94	5.12	2.47	8.23	4.32
		Weekend	2.29	1.18	5.49	3.20	8.15	5.67
		Extended	2.35	1.19	5.52	2.96	8.21	5.48
	6 in.	Nighttime	4.74	2.09	13.01	4.67	19.95	10.46
		Weekend	4.74	2.45	12.56	5.13	17.58	12.23
		Extended	4.79	2.43	13.00	5.87	17.93	11.96

4.2.6 Regression Analysis

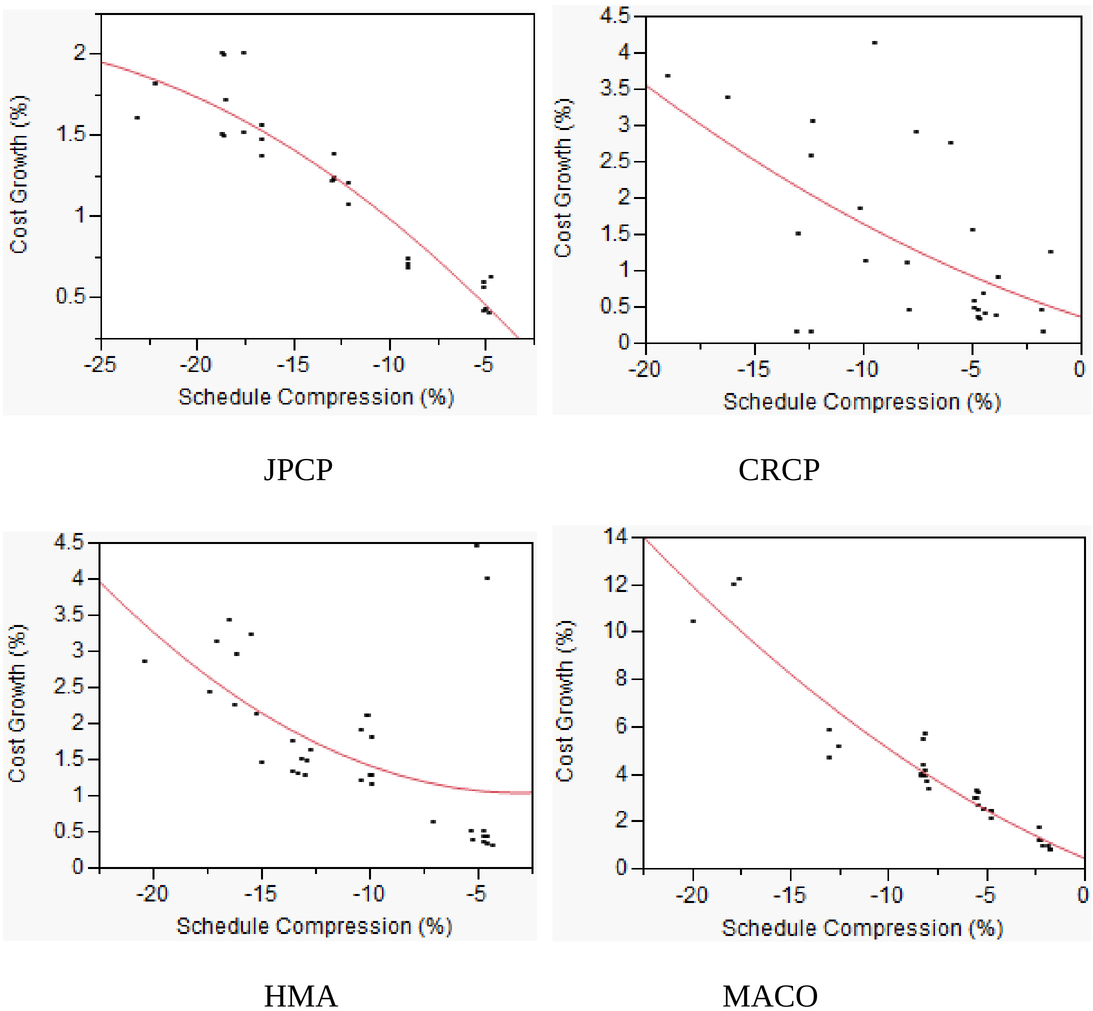


Figure 11. Time-Cost Tradeoff Curves

Figure 11 highlights the relationship between schedule compression and cost growth using data from Tables 6 – 13, which is denoted by a quadratic curve. As the assigned time for completing the project is shortened, the cost growth from the contractors' side increases. Hence, an inverse relation is witnessed between schedule compression and cost growth.

Table 14. Regression Analysis Results of JPCP

Model	Coefficient	Std. Error	t-value
Intercept	-0.1803	0.1822	0.3325
Time	-0.1378	0.0317	0.0002
Time * Time	-0.0021	0.0012	0.0991

From table 14, the F-ratio of 95.09 is significant at level 0.001, which suggest that the regression equation is adequate. The R-squared value of 0.8889 indicates a strong reasonable fit between time and cost. (* $p<0.05$, **$p<0.01$, ***$p<0.001$)

Table 15. Regression Analysis Results of CRCP

Model	Coefficient	Std. Error	t-value
Intercept	0.365	0.6898	0.6014
Time	-0.096	0.1719	0.5803
Time * Time	0.0032	0.0089	0.7279

From table 15, the F-ratio of 6.2156 is significant at level 0.001, which suggest that the regression equation is adequate. The R-squared value of 0.3412 indicates a strong reasonable fit between time and cost. (* $p<0.05$, **$p<0.01$, ***$p<0.001$)

Table 16. Regression Analysis Results of HMA

Model	Coefficient	Std. Error	t-value
Intercept	1.1133	0.1035	0.2062
Time	0.0469	0.0062	0.7942
Time * Time	0.0077	0.0012	0.3491

From table 16, the F-ratio of 6.5115 is significant at level 0.001, which suggest that the regression equation is adequate. The R-squared value of 0.2829 indicates a strong reasonable fit between time and cost. (* p<0.05, **p<0.01, ***p<0.001)

Table 17. Regression Analysis Results of MACO

Model	Coefficient	Std. Error	t-value
Intercept	0.4414	0.4397	0.3227
Time	-0.3507	0.1106	0.0033
Time * Time	0.0112	0.0055	0.0479

From table 17, the F-ratio of 170.5328 is significant at level 0.001, which suggest that the regression equation is adequate. The R-squared value of 0.9118 indicates a strong reasonable fit between time and cost. (* p<0.05, **p<0.01, ***p<0.001)

4.2.7 Initial I/D Amount Determination (Lower Bound) for JPCP

Tradeoff equation (quadratic equation) between schedule and cost is:

$\text{Cost} = -\,0.1803 - 0.1378\,(\text{time}) - 0.0021(\text{time})^2$

From equation 6 (final equation for CAC):

$\Delta C = -\,0.1378 - 0.0042\, t_1 - 0.0021\, \Delta T$, where $t_1 = t_0 - \Delta T$

Hence final equation is:

$\Delta C = -\,0.1378 - 0.0042\, t_0 + 0.0021\ \Delta T$

As specified earlier, incentive fees should satisfy the following relationship:

CAC ≤ I/D ≤ Discounted total savings to road users and the contracting agency,

Hence the final equation used for quantifying the lower bound of traffic (CAC) is summarized below:

($-\,0.1378 - 0.0042\, t_0 + 0.0021\ \Delta T$) ≤ I/D ≤ (Discounted total savings to road users and the contracting agency).

4.2.8 Initial I/D Amount Determination (Lower Bound) for CRCP

Tradeoff equation between schedule and cost is:

$\text{Cost} = 0.365 - 0.096\ (\text{time}) + 0.0032\ (\text{time})^2$

From equation 6:

$\Delta C = -\,0.096 + 0.0064\, t_1 + 0.0032\ \Delta T$, where $t_1 = t_0 - \Delta T$

Hence final equation is:

$\Delta C = -\,0.096 + 0.0064\, t_0 - 0.0032\ \Delta T$

As specified earlier, incentive fees should satisfy the following relationship:

CAC ≤ I/D ≤ Discounted total savings to road users and the contracting agency,

Hence the final equation used for quantifying the lower bound of traffic (CAC) is summarized below:

($-\,0.096 + 0.0064\, t_0 - 0.0032\ \Delta T$) ≤ I/D ≤ (Discounted total savings to road users and the contracting agency).

4.2.9 Initial I/D Amount Determination (Lower Bound) for HMA

Tradeoff equation between schedule and cost is:

$$\text{Cost} = 1.1133 + 0.0469\ (\text{time}) + 0.0077\ (\text{time})^2$$

From equation 6:

$$\Delta C = 0.0469 + 0.0154\, t_1 + 0.0077\ \Delta T, \text{ where } t_1 = t_0 - \Delta T$$

Hence final equation is:

$$\Delta C = 0.0469 + 0.0154\, t_0 - 0.0077\ \Delta T$$

As specified earlier, incentive fees should satisfy the following relationship:

CAC $\leq$ I/D $\leq$ Discounted total savings to road users and the contracting agency,

Hence the final equation used for quantifying the lower bound of traffic (CAC) is summarized below:

$(0.0469 + 0.0154\, t_0 - 0.0077\ \Delta T) \leq$ I/D $\leq$ (Discounted total savings to road users and the contracting agency).

4.2.10 Initial I/D Amount Determination (Lower Bound) for MACO

Tradeoff equation between schedule and cost is:

$$\text{Cost} = 0.4414 - 0.3507\ (\text{time}) - 0.0112\ (\text{time})^2$$

From equation 6:

$$\Delta C = -\,0.3507 + 0.0224\, t_1 + 0.0112\ \Delta T, \text{ where } t_1 = t_0 - \Delta T$$

Hence final equation is:

$\Delta C = -0.662 + 0.0224\, t_0 - 0.0112\, \Delta T$

As specified earlier, incentive fees should satisfy the following relationship:

CAC $\leq$ I/D $\leq$ Discounted total savings to road users and the contracting agency,

Hence the final equation used for quantifying the lower bound of traffic (CAC) is summarized below:

$(-0.662 + 0.0224\, t_0 - 0.0112\, \Delta T) \leq$ I/D $\leq$ (Discounted total savings to road users and the contracting agency.

The final quantifying equations for the four different pavements are mentioned below:

- JPCP $(-0.1378 - 0.0042\, t_0 + 0.0021\, \Delta T) \leq$ I/D $\leq$ (Discounted total savings to road users and the contracting agency).
- CRCP $(-0.096 + 0.0064\, t_0 - 0.0032\, \Delta T) \leq$ I/D $\leq$ (Discounted total savings to road users and the contracting agency).
- HMA $(0.0469 + 0.0154\, t_0 - 0.0077\, \Delta T) \leq$ I/D $\leq$ (Discounted total savings to road users and the contracting agency).
- MACO $(-0.662 + 0.0224\, t_0 - 0.0112\, \Delta T) \leq$ I/D $\leq$ (Discounted total savings to road users and the contracting agency.

4.3 STEP 3: Quantification of Savings in Road User Cost for Establishing Lower Bound

The IDEF0 flowchart shown in figure 12 signifies the Quantification of savings in RUC using guidelines of the demand capacity model and concepts of RUC.

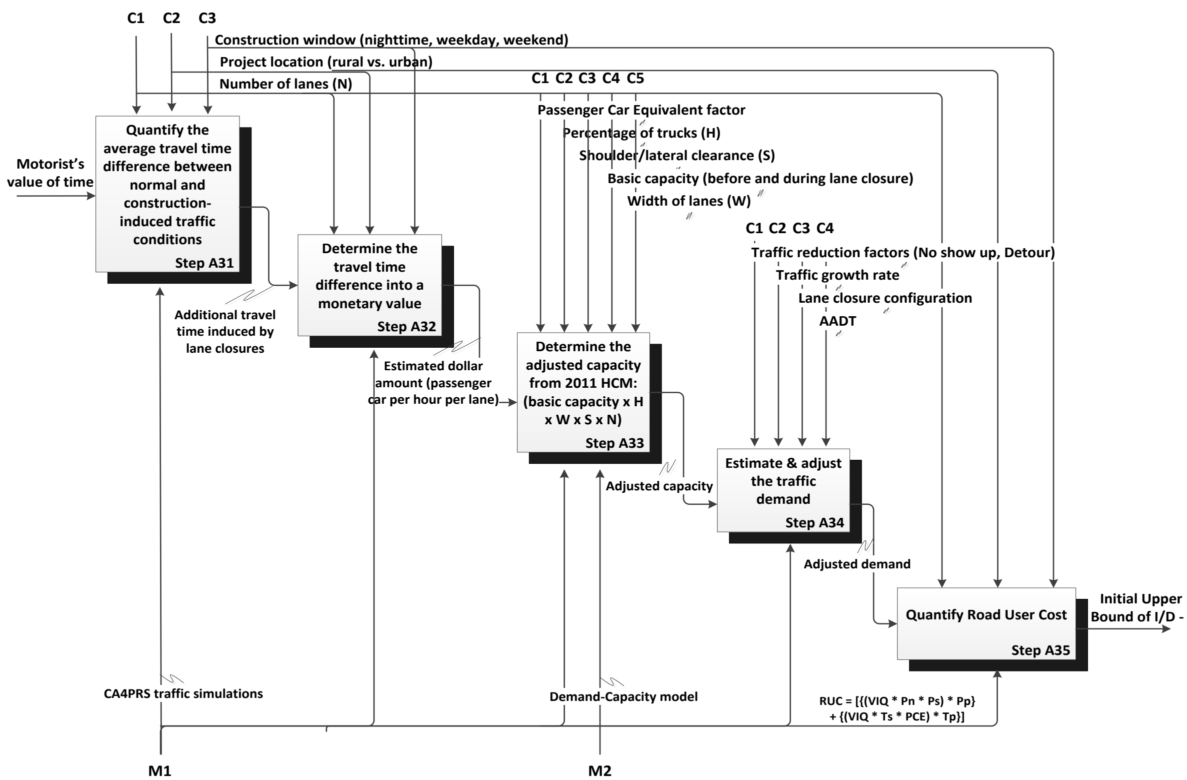


Figure 12. IDEF0 Flowchart Highlighting Quantification of Savings in RUC

4.3.1 Guidelines for Demand and Capacity

The Time-Value Saving Module incorporates the concept of demand-capacity model to determine Road User Costs (RUC), based on the Highway Capacity Manual 2000 (HCM, 2000). Demand is defined as hourly traffic volumes at a certain point of interest, which is unknown and thus requires the logical quantification presented in this section. Capacity is defined as the maximum possible traffic service flow, which can be selected from the manual.

4.3.2 Basic Capacity

In general, the capacity in CWZ areas is assumed to be close to 65-70% that of normal conditions (measured in pcphpl i.e. passenger car per hour per lane). A passenger car equivalent (PCE) of 1.5 is generally assumed for trucks for calculation purposes. Some of factors according due to which the capacity varies are mentioned below in Figure 13.

4.3.3 Adjusted Capacity

Adjusted Capacity is calculated by multiplying the capacity calculated in Step A32 by the four factors specified in Figure 12.

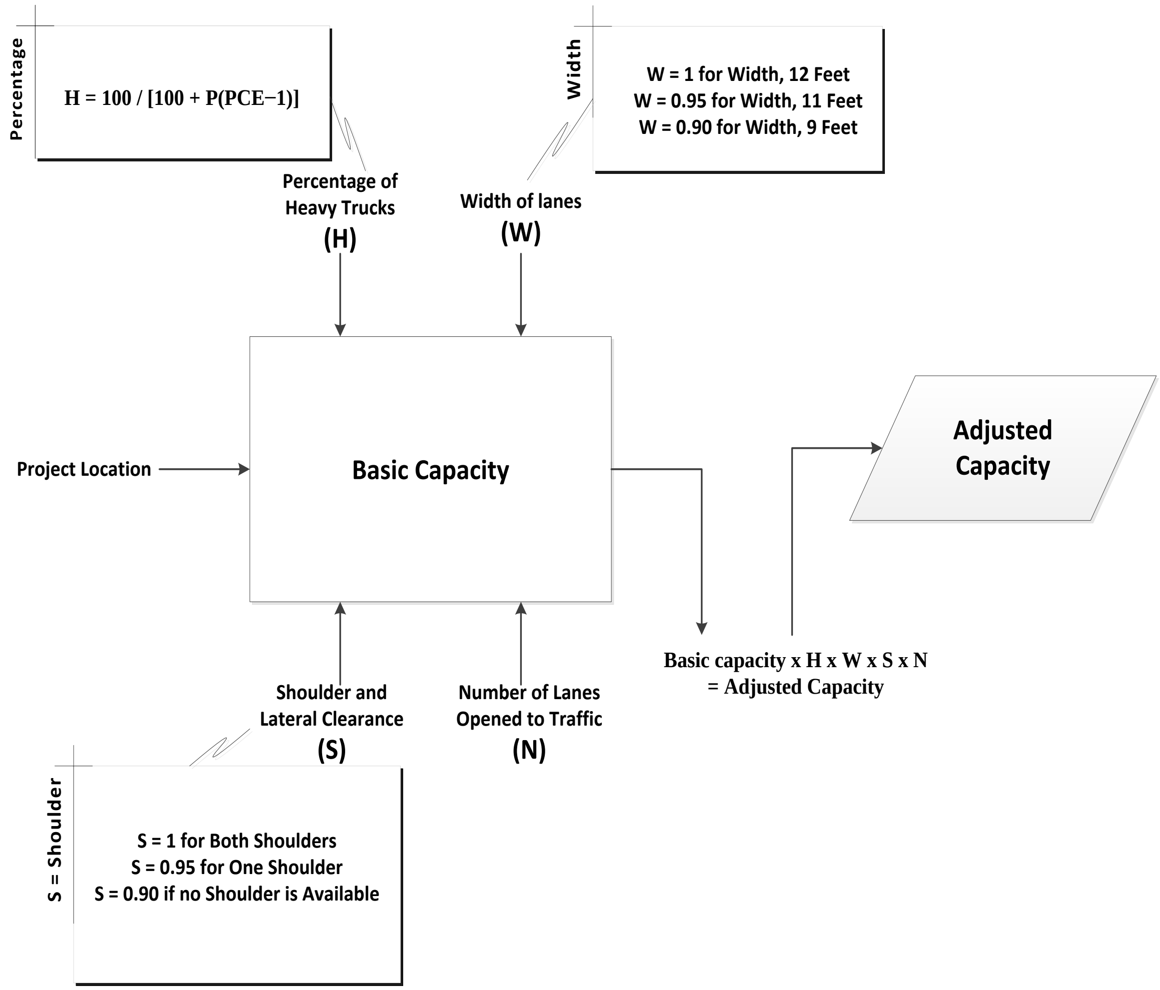


Figure 13. Determination of Adjusted Capacity from Basic Capacity

4.3.4 Factors Affecting Road User Cost

Figure 14 shows the four major factors which need to be taken into account when estimating Road User Cost:

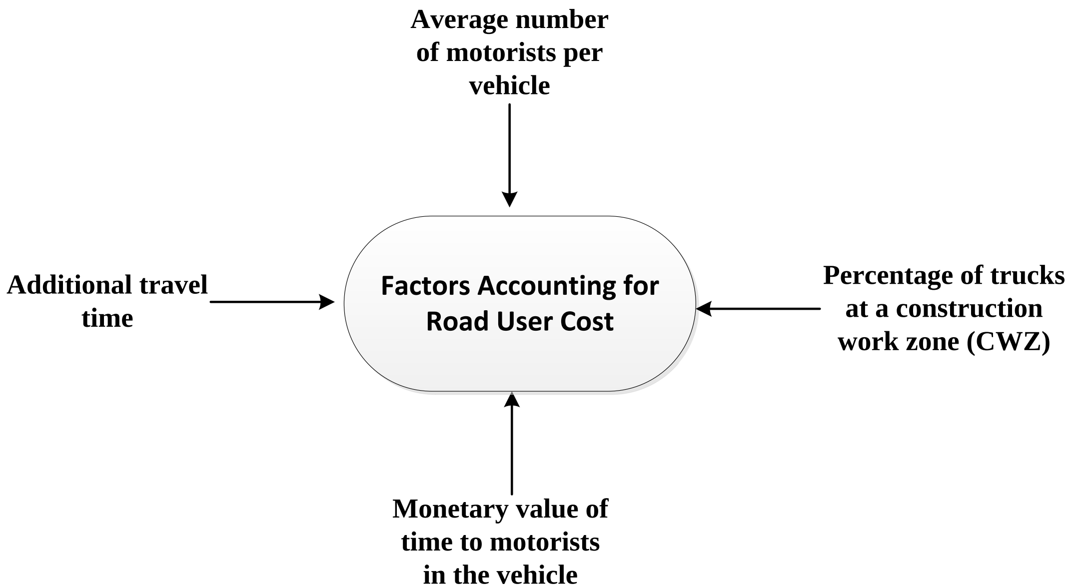


Figure 14. Factors Affecting RUC

The travel-time changes arise from differences in average travel time at the CWZ in two different traffic conditions, i.e., traffic conditions before construction and its predicted condition during construction, when normal flow is disrupted by lane closures for construction. The value of motorists' wasted time (cost per hour) on the roadway should be considered as a key parameter in the calculation of RUC. Different pay rates should also be applied to passenger cars and trucks.

4.3.5 Road User Cost Calculation – Initial Upper Bound I

Following flowchart shown in figure 15 describes the time-value saving module which computes the RUC using the following procedure:

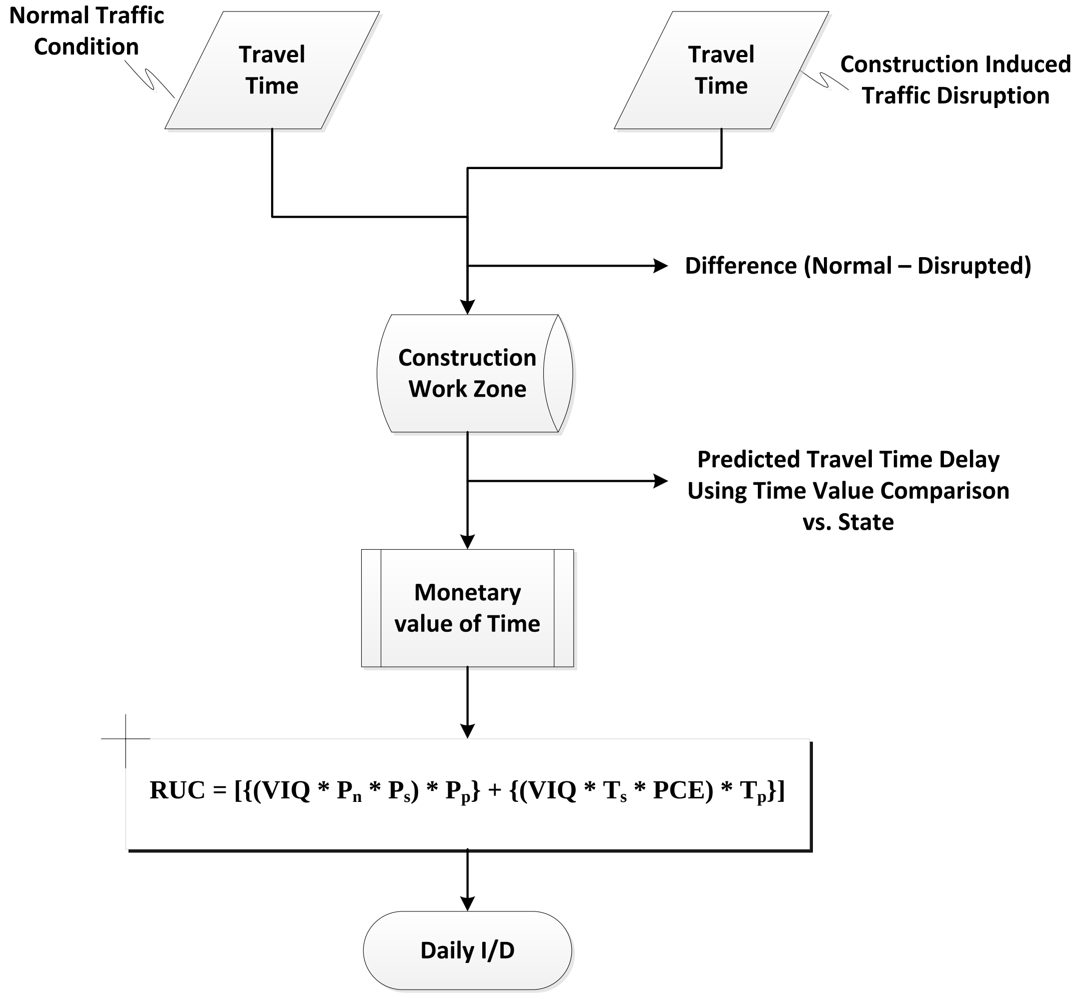


Figure 15. Time-Value Saving Module

Table 18 highlights the monetary value of time per hour across various states, both for automobiles and trucks. Table 18 is immediately followed by the RUC equation which depends on a number of factors which are specified below.

Table 18. Time Value Comparison vs. State

State	Average Time Value Automobiles ($)	Average Truck Value Trucks ($)
California	11.51	27.83
Florida	11.12	22.36
Georgia	11.65	N/A
New York	9.00	21.14
North Carolina	8.70	N/A
Ohio	12.60	26.40
Oregon	16.31	29.00
Pennsylvania	12.21	24.18
Texas	11.97	21.87
Virginia	11.97	21.87
Washington	12.51	50.00

$$RUC = [\{(VIQ * P_n * P_s) * P_p\} + \{(VIQ * T_s * PCE) * T_p\}]$$

Where, VIQ = anticipated number of vehicles in queue due to a construction delay

P_n = average number of passengers per passenger vehicle

P_s = monetary time value per passenger for passenger vehicles

P_p = percentage of passenger vehicles driving through the CWZ

T_s = average pay rate per hour for trucks

PCE = passenger car equivalent factor, it is generally assumed that a truck is equal to 1.5 passenger vehicles

T_p = percentage of trucks driving through the CWZ

In order for the SHAs to determine I/D dollar amount for the upper bound under budget limitations, the time value to road users should be adjusted downward by applying a realistic discount factor in an economically rational manner under the appropriate circumstances as is considered in the Time-Cost Tradeoff Module. Step 5 in the next few sections highlights the adjustment of I/D dollar amount with Level of Service (LOS).

Version 2.5 of CA4PRS was used to perform the work zone analysis in terms of road user cost and time spent in queue. The work zone analysis module of CA4PRS is based on the demand-capacity concept already described in the above mentioned sections. Using the latest version of CA4PRS, lookup tables of road user costs were developed for use as a database in the Time-Value Saving Module. It is believed that this alternative way of using CA4PRS can considerably reduce the effort, time, and future development costs of a prototype computer software system.

Figure 16 highlights the factors significantly affecting the value of RUC as incorporated using CA4PRS:

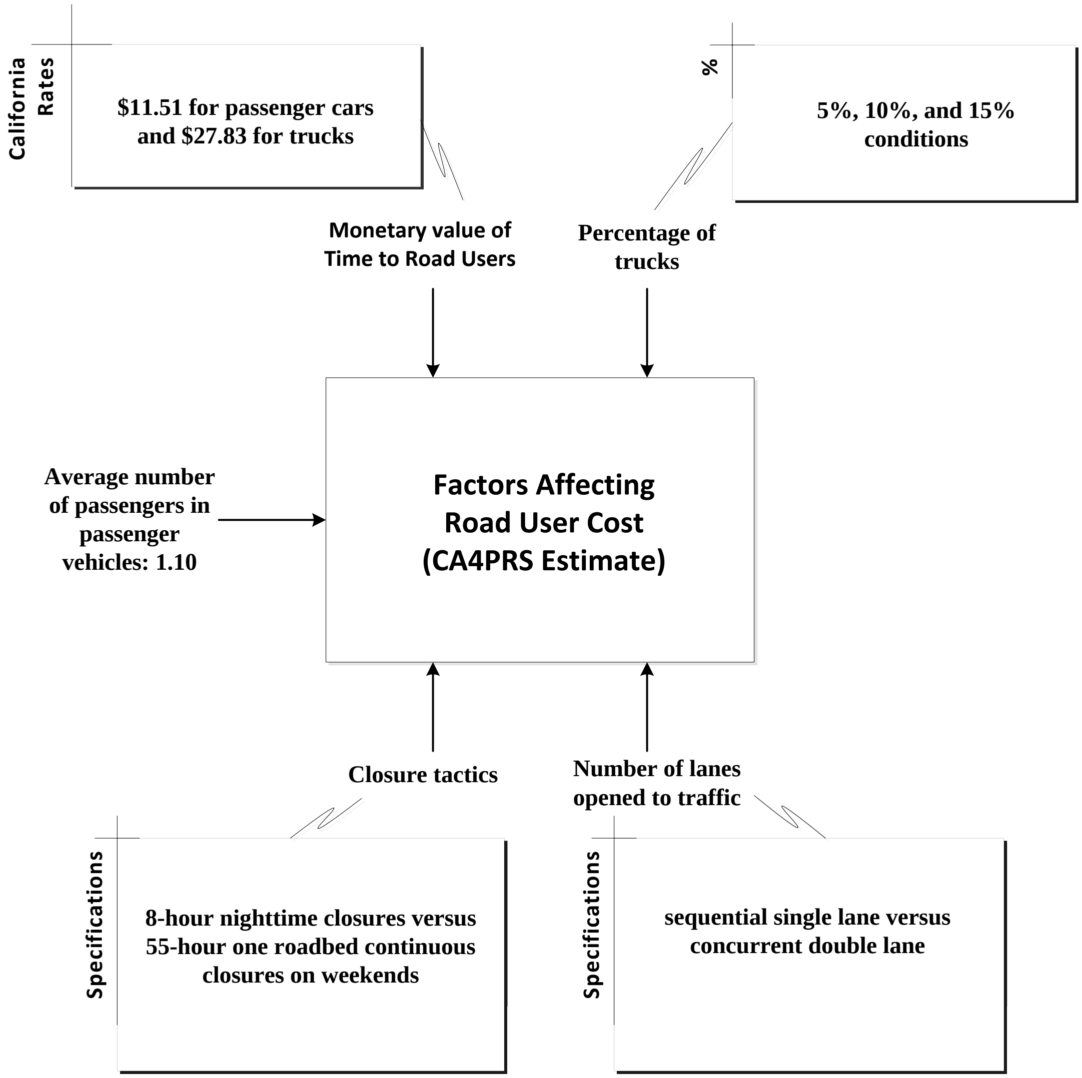


Figure 16. Factors Affecting RUC (CA4PRS Estimate)

The following tables (19-21) highlight the RUC calculations per hour for automobiles and trucks by taking into account nighttime, weekday, weekend, partial and full closure lane tactics into account.

Table 19. RUC Calculation for a 4 by 4 Urban Freeway: Nighttime Construction Project with Partial Closure

Partial Closure: 8-hour Nighttime Construction* Two Lane Closed in One Direction		
AADT	5% Trucks	10% Trucks
50,000	549	590
55,000	605	649
60,000	660	709
65,000	714	767
70,000	769	826
75,000	824	886
80,000	879	945
85,000	934	1,003
90,000	990	1,063
95,000	1,044	1,122
100,000	1,099	1,181
105,000	1,154	1,240
110,000	1,209	1,299
115,000	1,264	1,358
120,000	1,318	1,418
125,000	1,374	1,476
130,000	1,429	1,535
135,000	1,484	1,595
140,000	1,539	1,653
145,000	1,593	1,712
150,000	1,648	1,772
155,000	2,084	2,770
160,000	2,814	3,587
165,000	3,590	4,462
170,000	4,412	5,408
175,000	5,319	6,439
180,000	6,297	7,575
185,000	7,375	8,844
190,000	8,577	14,466
195,000	14,330	23,215
200,000	22,632	38,727

Table 20. RUC Calculation for a 4 by 4 Urban Freeway: Weekend Construction Project with Full Closure

Extended Full Closure: 55-hour Weekend Construction* Counter Flow Traffic (One Direction Closed Completely)				
AADT	5% Trucks		10% Trucks	
	Per Day	Per Closure	Per Day	Per Closure
50,000	5,208	11,935	5,584	12,797
55,000	5,730	13,131	6,142	14,075
60,000	6,250	14,323	6,250	14,323
65,000	6,772	15,519	7,250	16,615
70,000	7,292	16,711	7,818	17,916
75,000	7,813	17,905	8,376	19,195
80,000	8,334	19,099	8,934	20,474
85,000	8,854	20,290	9,492	21,753
90,000	9,375	21,484	10,051	23,034
95,000	9,896	22,678	10,609	24,312
100,000	13,788	31,598	22,965	52,628
105,000	38,298	87,766	67,217	154,039
110,000	112,762	258,413	201,051	460,742
115,000	280,932	643,803	425,126	974,247
120,000	526,347	1,206,212	725,545	1,662,707
125,000	823,566	1,887,339	1,065,467	2,441,695
130,000	1,148,759	2,632,573	1,419,503	3,253,028
135,000	1,489,249	3,412,862	1,792,609	4,108,062
140,000	1,840,156	4,217,024	2,180,459	4,996,885
145,000	2,211,146	5,067,210	2,580,652	5,913,994
150,000	2,587,398	5,929,454	2,993,502	6,860,109
155,000	2,980,721	6,830,819	3,421,222	7,840,300
160,000	3,382,703	7,752,028	3,852,581	8,828,831
165,000	3,788,026	8,680,893	4,287,627	9,825,812
170,000	4,196,736	9,617,520	4,726,411	10,831,359
175,000	4,608,877	10,562,010	5,178,043	11,866,349
180,000	5,037,978	11,545,366	5,661,729	12,974,796
185,000	5,492,116	12,586,099	6,149,647	14,092,941
190,000	5,950,137	13,635,731	6,641,860	15,220,929
195,000	6,412,096	14,694,387	7,138,426	16,358,893
200,000	6,878,045	15,762,186	7,639,408	17,506,977

.

Table 21. RUC Calculation for a 4 by 4 Urban Freeway: Weekday Construction Project with Full Closure

Extended Full Closure: 72-hour Weekday Construction* Counter Flow Traffic (One Direction Closed Completely)				
AADT	5% Trucks		10% Trucks	
	Per Day	Per Closure	Per Day	Per Closure
50,000	5,208	15,624	5,584	16,752
55,000	5,730	17,190	6,142	18,426
60,000	6,250	18,750	6,700	20,100
65,000	6,771	20,313	7,259	21,777
70,000	7,292	21,876	7,817	23,451
75,000	7,813	23,439	8,376	25,128
80,000	8,334	25,002	11,993	35,979
85,000	18,653	55,959	26,283	78,849
90,000	36,717	110,151	49,675	149,025
95,000	65,343	196,029	94,277	282,831
100,000	126,389	379,167	175,151	525,453
105,000	216,444	649,332	283,134	849,402
110,000	329,857	989,571	423,533	1,270,599
115,000	506,031	1,518,093	673,626	2,020,878
120,000	763,178	2,289,534	971,842	2,915,526
125,000	1,064,916	3,194,748	1,326,539	3,979,617
130,000	1,412,261	4,236,783	1,742,541	5,227,623
135,000	1,826,961	5,480,883	2,267,442	6,802,326
140,000	2,284,979	6,854,937	2,793,000	8,217,000
145,000	2,791,654	8,374,962	3,292,015	9,876,045
150,000	3,312,240	9,936,720	3,849,620	11,548,860
155,000	3,836,114	11,508,342	4,418,417	13,255,251
160,000	4,376,824	13,130,472	5,040,521	15,121,563
165,000	4,969,943	14,909,829	5,679,247	17,037,741
170,000	5,569,840	16,709,520	6,322,571	18,967,713
175,000	6,173,958	18,521,874	6,970,556	20,911,668
180,000	6,782,354	20,347,062	7,623,267	22,869,801
185,000	7,395,086	22,185,258	8,289,514	24,868,542
190,000	8,022,295	24,066,885	8,972,350	26,917,050
195,000	8,663,094	25,989,282	9,660,298	28,980,894
200,000	9,308,577	27,952,731	10,353,433	31,060,894

4.4 STEP 4: Quantification of Savings in Agency Cost Using Schedule Compression Rates

Figure 17 highlights the three major factors affecting monetary time value savings which in turn are crucial for calculating the agency cost savings. These are construction zone enhanced enforcement program, agency engineering cost, and movable concrete barrier.

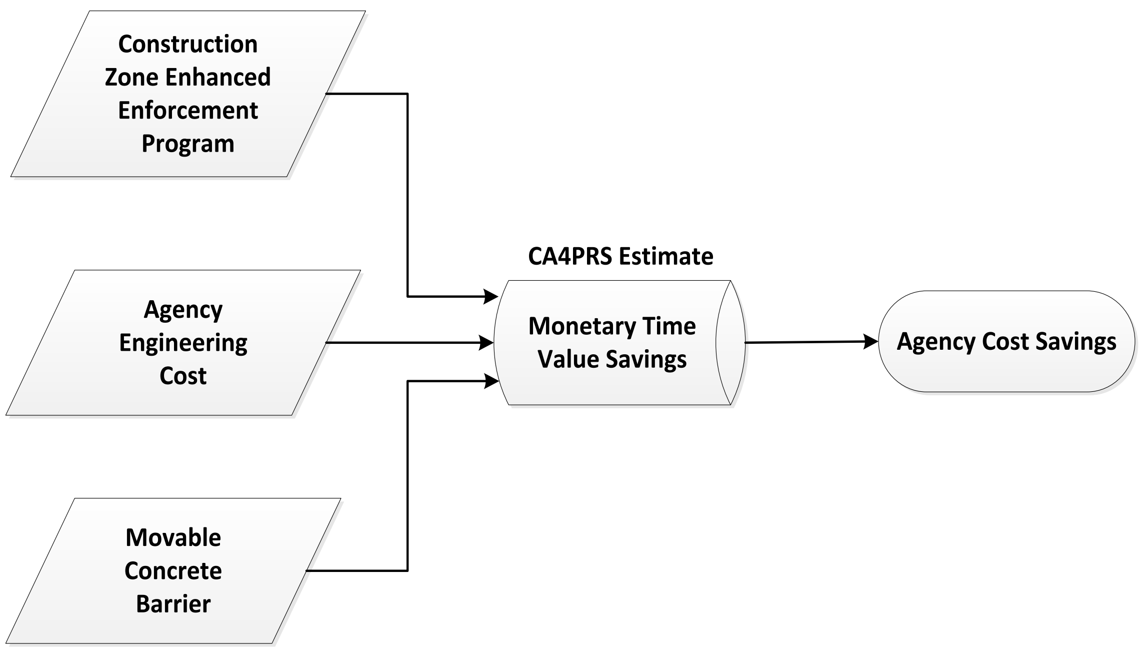


Figure 17. Quantification of Savings in Agency Costs

4.4.1 Agency Cost Savings

The contracting agencies can also save considerable amount of agency costs as a result of shortened construction schedule. The savings include reductions in the cost of construction zone enhanced enforcement program (COZEEP), agency engineering cost (AEC), and moveable concrete barrier (MCB) rental. The total agency costs can be quantified by adding up the above mentioned three major costs.

Table 22 shows a list of agency cost saving factors and displays methods to quantify their monetary value. The daily rates and methods in Table 22 are imported directly from the CA4PRS cost estimate outline.

Table 22. CA4PRS Agency Cost Saving Calculation Factors and Methods

Factors	Rates	Methods
COZEEP	▪ $700/day/officer ▪ Number of officers - 2.5/day for nighttime - 4.5/day for extended closure ▪ Overtime rate of 1.2	▪ CHP cost/day x # number of days saved x overtime rate x 3 shifts for extended closure
Agency Engineering Cost (AEC)	▪ $320/day/staff ▪ Number of staff - 3/day for nighttime - 4/day for extended closure with 3 shifts ▪ Overtime rate - 1.1 for nighttime - 1.5 for extended closure	▪ Staffing cost/day x # of staff/day x number of days x overtime rate x 3 shifts for extended closure
MCB	▪ Barrier cost - $60/meter for the first month - $11/meter for the second month ▪ Transformer cost - $30,000 for the first month - $15,000 for the second month	▪ Center-lane-meter to set up x appropriate monthly rates

*MCB cost applies to the extended closure only

4.4.2 Monetary Time Value Savings – Initial Upper Bound II

Table 23 shows monetary time values saved to the agency, made on the basis of the CA4PRS cost estimate outline.

Table 23. Calculation of Agency Cost Savings

Days Saved A	Nighttime Construction		Total Savings ($) D	Extended Constrution		Total Savings[c] ($) G
	COZEEP[a]($) B	AAC[b] ($) C		COZEEP($) E	AAC ($) F	
1	2,100	1,056	3,156	11,340	5,760	17,100
2	4,200	2,112	6,312	22,680	11,520	34,200
3	6,300	3,168	9,468	34,020	17,280	51,300
4	8,400	4,224	12,624	45,360	23,040	68,400
5	10,500	5,280	15,780	56,700	28,800	85,500
6	12,600	6,336	18,936	68,040	34,560	102,600
7	14,700	7,392	22,092	79,380	40,320	119,700
8	16,800	8,448	25,248	90,720	46,080	136,800
9	18,900	9,504	28,404	102,060	51,840	153,900
10	21,000	10,560	31,560	113,400	57,600	171,000
11	23,100	11,616	34,716	124,740	63,360	188,100
12	25,200	12,672	37,872	136,080	69,120	205,200
13	27,300	13,728	41,028	147,420	74,880	222,300
14	29,400	14,784	44,184	158,760	80,640	239,400
15	31,500	15,840	47,340	170,100	86,400	256,500
16	33,600	16,896	50,496	181,440	92,160	273,600
17	35,700	17,952	53,652	192,780	97,920	290,700
18	37,800	19,008	56,808	204,120	103,680	307,800
19	39,900	20,064	59,964	215,460	109,440	324,900
20	42,000	21,120	63,120	226,800	115,200	342,000
21	44,100	22,176	66,276	238,140	120,960	359,100
22	46,200	23,232	69,432	249,480	126,720	376,200
23	48,300	24,288	72,588	260,820	132,480	393,300
24	50,400	25,344	75,744	272,160	138,240	410,400
25	52,500	26,400	78,900	283,500	144,000	427,500
26	54,600	27,456	82,056	294840	149,760	444,600
27	56,700	28,512	85,212	306,180	155,520	461,700
28	58,800	29,568	88,368	317,520	161,280	478,800
29	60,900	30,624	91,524	328,860	167,040	495,900
30	63,000	31,680	94,680	340,200	172,800	513,000

COZEEP[a]: Construction Zone Enhanced Enforcement Program, AAC[b]: Agency Administrative Cost, Column (D) = Column (B) + Column (C), Column (G) = Column (E) + Column (F)

4.5 STEP 5: Contractors' Additional Cost Adjustment with Level of Service (LOS)

Figure 18 highlights the different procedures we need to follow to calculate the CAC adjustments using the concept of level of service.

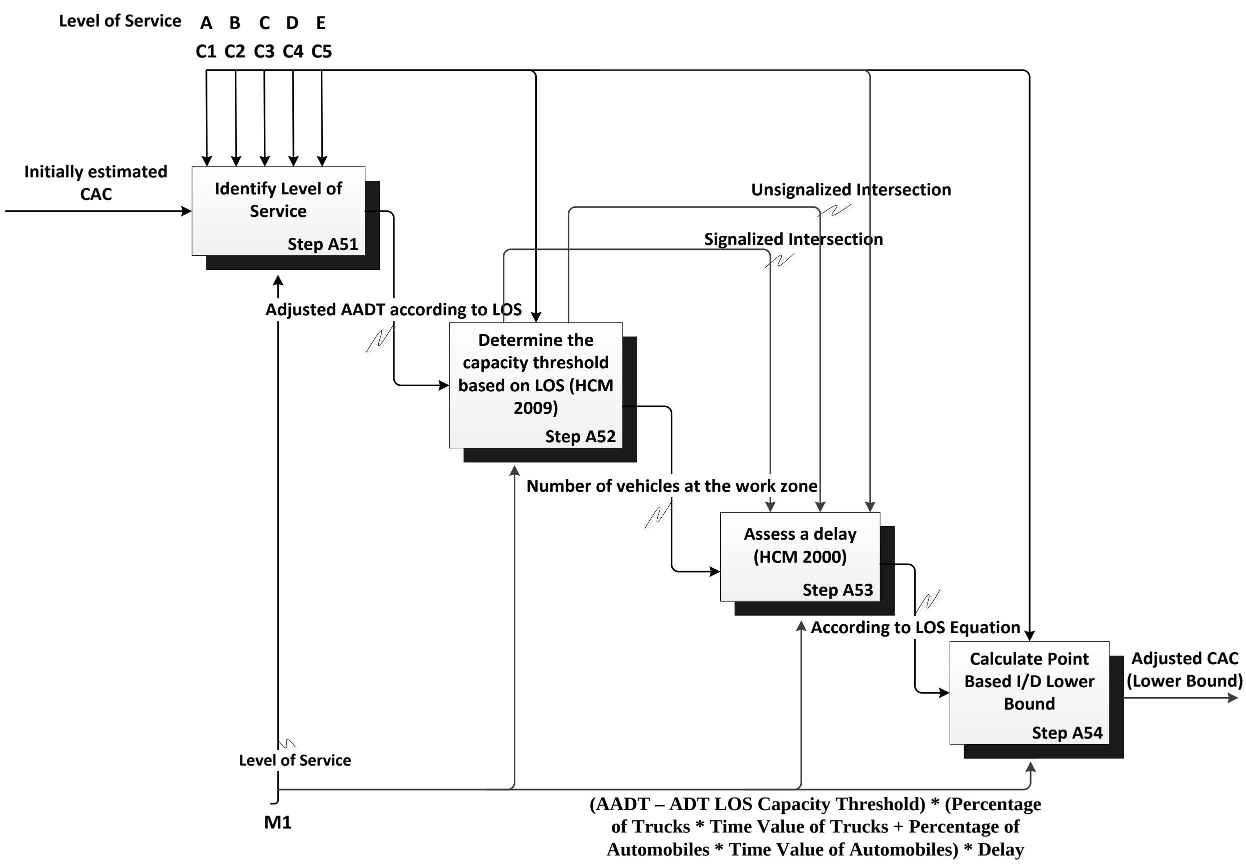


Figure 18. IDEF0 Framework for Determining Adjusted Lower Bound Using LOS

4.5.1 Level of Service

LOS is used to measure and describe the operational effectiveness of a roadway section undergoing rehabilitation/renewal work. LOS A is the best performing service which indicates free flow of traffic with little or no delay, whereas LOS F is the worst service accompanied by traffic flows exceeding the capacity, thereby resulting in long queues and delays.

4.5.2 Average Daily Traffic

As already specified earlier (Table 19 – Table 21), Annual Average Daily Traffic (AADT) is the total volume of traffic accompanying any roadway/highway throughout the year divided by 365 days. Table 24 highlights different types of LOS thresholds as specified in the Highway Capacity Manual. Average Daily Traffic (ADT) is the total number of vehicles passing through a given point measured over a course of time period ranging from 2 to 365 days.

Table 24. LOS Definitions for Roadway Segments

Roadway Classification	Number of Lanes	ADT Level of Service Capacity Threshold				
		A	B	C	D	E
Minor Arterial	2	9,000	10,700	12,000	13,500	15,000
Collector Street	2	5,250	6,125	7,000	7,875	8,750
Local Street	2	-	-	3,000	4,000	5,000

Source: Fehr & Peers 2009, based on the *Highway Capacity Manual*, Transportation Research Board, 2000 and internal Fehr & Peers research.

4.5.3 Delay

Table 25 shows the relationship between delay and LOS for signalized and unsignalized intersections. Signalized intersections use various intersection characteristics such as traffic volumes, lane geometry, and signal phasing to estimate the average control delay per vehicle. On the other hand, unsignalized intersections incorporate all-way stop-controlled and side-street stop-controlled evaluations.

Table 25. Intersection Level of Service Criteria

Level of Service	Signalized Intersection Control Delay per Vehicle (Seconds)	Unsignalized Intersection Control Delay per Vehicle (Seconds)
A	≤ 10.0	≤ 10.0
B	> 10.0 and ≤ 20.0	> 10.0 and ≤ 15.0
C	> 20.0 and ≤ 35.0	> 15.0 and ≤ 25.0
D	> 35.0 and ≤ 55.0	> 25.0 and ≤ 35.0
E	> 55.0 and ≤ 80.0	> 35.0 and ≤ 50.0
F	> 80.0	> 50.0

Source: *Highway Capacity Manual – Special Report 209* (Transportation Research Board, 2000)

This study uses signalized intersections to calculate the discounting factors to determine point based I/D amount.

4.5.4 Adjusted I/D for Lower Bound

Using the equation mentioned below, savings associated with LOS for any given roadway profile can be calculated.

(AADT – ADT LOS Capacity Threshold) * (Percentage of Trucks * Time Value of Trucks + Percentage of Automobiles * Time Value of Automobiles) * LOS Delay

The I/D amount calculated from contractors' additional cost growth (CAC) is then added to the savings generated from LOS to arrive at point based estimates of I/D.

4.6 STEP 6: Total Savings Adjustment using Net Present Value (NPV)

Figure 19 highlights the different procedures we need to follow to calculate total savings adjustment using the concept of net present value..

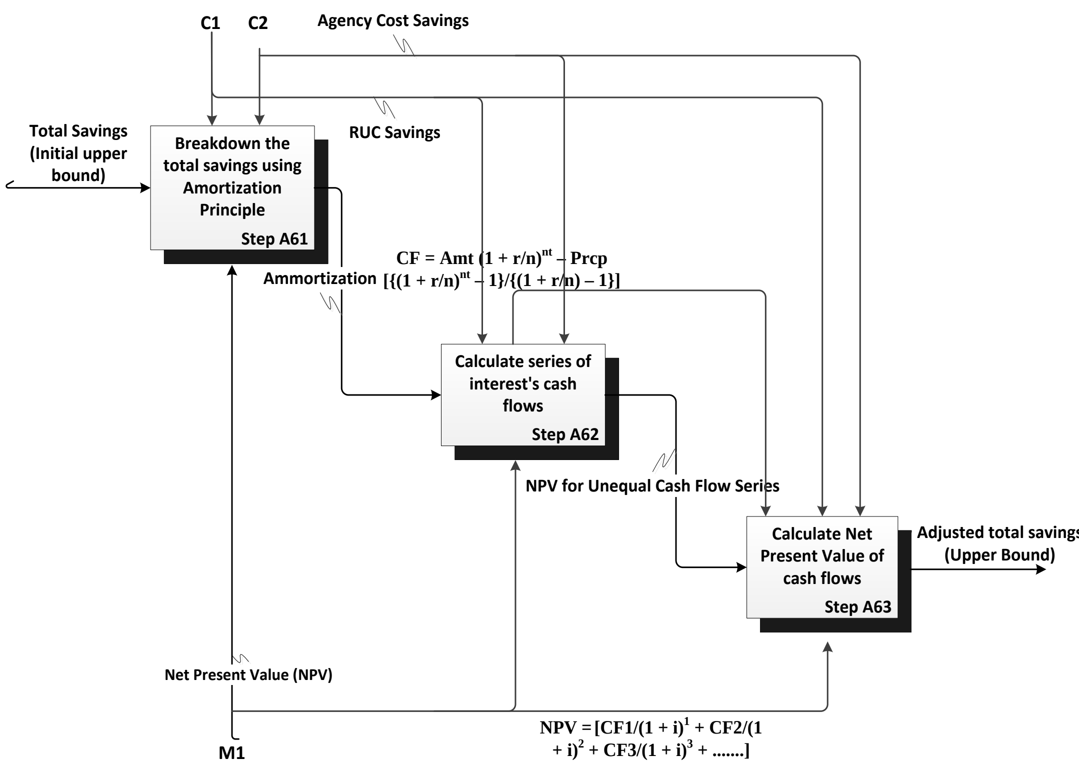


Figure 19. IDEF0 Framework for Determining Adjusted Upper Bound Using NPV

4.6.1 Calculate Difference between Project Budget and Total Savings

NPV is briefly described as today's worth of a future amount of money, before interest earnings and charges. For this study, NPV of the interest accumulated over a period of time is considered as the baseline for calculating the upper bound. STAs by finishing the projects early are able to bring down the RUC and agency costs, which indirectly results in lowering the projects' budget. RUC savings and agency cost savings generated from Steps 3and 4 respectively, can be combined to form the total savings.

4.6.2 Calculate Accumulated Interest

These total savings are indirectly the amount which the STAs would have borrowed otherwise from the funding agencies, had there been no savings. Hence these total savings can be assumed as a loan amount accruing interest every year till the yearly payments are over. The following compounding equation can be used to calculate the interest accrued each year.

$$CF = \text{Amount } (1 + r/n)^{nt} - \text{Principal } [\{(1 + r/n)^{nt} - 1\}/\{(1 + r/n) - 1\}]$$

Where,

CF = Cash Flow (Total balance after t years)

Amount = Total amount borrowed

n = number of payments

Principal = Principal amount paid per payment

r = rate of interest

4.6.3 Net Present Value of Cash Flows

The interest accrued each year can be arranged to form a series of cash flows. Using the formula of Net Present Value specified below, NPV of the total cash flows (Interest payments each year) can be calculated.

$$NPV = [CF1/(1 + i)^1 + CF2/(1 + i)^2 + CF3/(1 + i)^3 + \ldots\ldots]$$

Where,

i is the rate of return per period;

CF1 is the cash flow during the first period;

CF2 is the cash flow during the second period;

CF3 is the cash flow during the third period, and so on...

The NPV of the interest payments accrued each year will be the point based estimate of I/D for the upper bound.

4.7 STEP 7: Determine I/D between Adjusted CAC and Total Savings

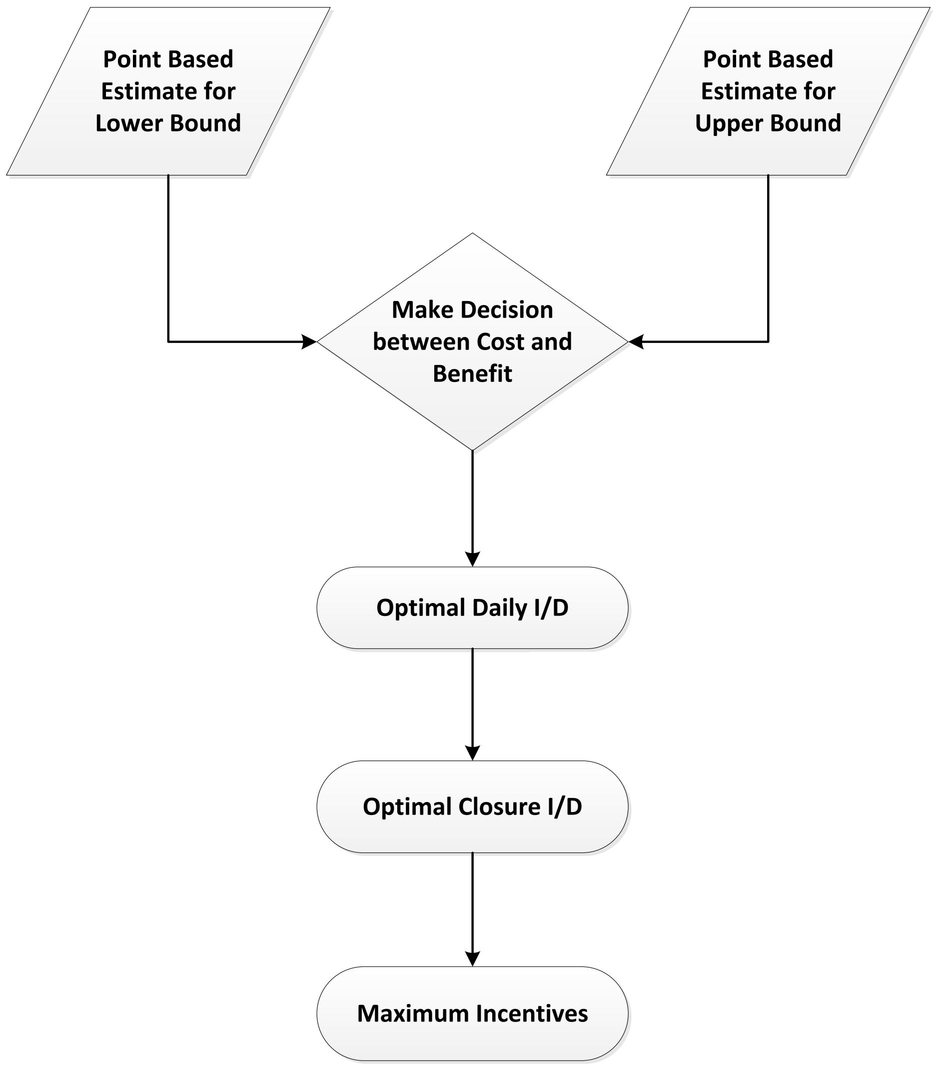


Figure 20. Decision Making between Cost and Benefit

Using the comparison shown in figure 20, arrive at a decision regarding the implementation of I/D based on the comparison of CAC using LOS and total savings using NPV (Cost vs. Benefit).

The final I/D dollar amount should be more than the contractors' additional cost growth for expediting construction time, and at the same time should be less than benefits on the part of the agency in terms of road user cost and agency cost. Based on the discounting factors derived from the concept of level of service and net present value for lower and upper bounds respectively, an optimal decision can be reached for determining point based I/D amounts.

The optimal daily I/D dollar amount established after making a decision between cost and benefit (lower bound vs. upper bound) is then multiplied by the number of closures (imported from CA4PRS) to arrive at the optimal closure I/D.

5 VALIDATION STUDIES

5.1 I-15 Devore Project (Data from CA4PRS)

The scope of I-15 Devore project was to rebuild 4.5 km stretch of two badly damaged truck lanes. The model developed was used to examine whether I/D strategies would be appropriate for this project, and if so, what could be the realistic I/D amount. The AADT for the project is approximately 100,000 vehicles and percentage of trucks at the CWZ is 10%. Lane closure scheme for the project was double lane closure with counter-flow traffic and extended weekday closures with around the clock operations were employed. Pavement thickness for the project was 12 in. with 6 in. asphalt concrete base.

5.1.1 Validation of Step 1 and 2 (I-15)

From the time-cost tradeoff curve for JPCP, the schedule compression rate is determined as -0.166 (16.6% reduction). Hence from the equation for determining CAC, the final figure in terms of lower bound comes out be:

The results prove that the project is appropriate for using I/D provision since the lower bound is smaller than the total savings in terms of RUC and Agency Cost.

JPCP:

$– 0.1378 – 0.0042\, t_0 + 0.0021\, \Delta T = – 0.1378 – 0.0042\,(1) – 0.0021\,(.166) = 0.1423\% =$ \$25,614/day (\$76,842/closure)

CRCP:

$-0.096 + 0.0064\,t_0 - 0.0032\ \Delta T = -0.096 + 0.0064\,(1) + 0.0032\ (0.166) = 0.0891\% =$ \$16,038/day (\$48,114/closure)

HMA:

$0.0469 + 0.0154\,t_0 - 0.0077\ \Delta T = 0.0469 + 0.0154\,(1) + 0.0077\ (0.166) = 0.0635\% =$ \$11,430/day (\$34,290/closure)

MACO:

$-0.662 + 0.0224\,t_0 - 0.0112\ \Delta T = -0.662 + 0.0224\,(1) + 0.0112\ (0.166) = -0.6378\% =$ \$114,804/day (\$344,412/closure)

5.1.2 Validation of Step 3 and 4 (I-15)

Using CA4PRS data from Table 3, it would require approximately 4 working days (1.3 closures) less if I/D contracting strategy are applied. From the RUC Table 21, the expected daily savings to road users comes out to be \$175,151 and in terms of closures, the savings is expected to be \$525,453. The expected savings in terms of agency cost comes out to be \$68,400 (\$205,200 per closure), based on monetary value calculation shown in Table 23.

Table 26 shows the results of Steps 1, 2, 3 and 4 in the form of upper and lower bounds of I/D before applying the Cost vs. Benefit decision making approach.

Table 26. Initial Lower and Upper Bounds of I/D (I-15)

	ΔC (JPCP)	ΔC (CRCP)	ΔC (HMA)	ΔC (MACO)	Savings to road users	Savings to the agency	Total Savings
Daily I/D	$25,614	$16,038	$11,430	$114,804	$175,151	$68,400	$243,551
Closure I/D	$76,842	$48,114	$34,290	$344,412	$525,453	$205,200	$730,653

From Table 26, it is very clear that the incentive cap should between CAC (ΔC) and total savings (RUC + Agency Cost), but the difference between the two amounts is incredibly high and henceforth, there is a huge need to come up with certain appropriate discounting factors which will help in arriving at point based I/D estimates.

5.2 I-710 Long Beach Project

The scope of the project was to reconstruct approximately 26 lane-km of existing pavement using 55-hour weekend closures. The project consisted of three dull-depth asphalt concrete (FDAC) replacement sections under freeway overpasses, and two sections with crack, seal, and overlay (CSOL) of existing PCC slabs with asphalt concrete. The AADT for the project is approximately 120,000 and percentage of trucks in the CWZ is 5%. Concurrent double lane closures with counter-flow traffic were the lane closure scheme adopted for this project.

5.2.1 Validation of Step 1 and 2 (I-710)

From the time-cost tradeoff curve for CRCP, the schedule compression rate is determined as -0.166 (16.6% reduction). Hence from the equation for determining CAC, the final figure in terms of lower bound comes out be:

The results prove that the project is appropriate for using I/D provision since the lower bound is smaller than the total savings in terms of RUC and AC.

JPCP:

$-0.1378 - 0.0042\,t_0 + 0.0021\ \Delta T = -0.1378 - 0.0042\,(1) - 0.0021\ (.166) = 0.1423\% =$ \$23,764/day (\$54,420/closure)

CRCP:

$-0.096 + 0.0064\,t_0 - 0.0032\ \Delta T = -0.096 + 0.0064\,(1) + 0.0032\ (0.166) = 0.0891\% =$ \$14,880/day (\$34,075/closure)

HMA:

$0.0469 + 0.0154\,t_0 - 0.0077\ \Delta T = 0.0469 + 0.0154\,(1) + 0.0077\ (0.166) = 0.0635\% =$ \$10,605/day (\$24,285/closure)

MACO:

$-0.662 + 0.0224\,t_0 - 0.0112\ \Delta T = -0.662 + 0.0224\,(1) + 0.0112\ (0.166) = 0.6378\% =$ \$106,513/day (\$243,915/closure)

5.2.2 Validation of Step 3 and 4 (I-710)

Using CA4PRS data from Table 2, it would require approximately 4 working days (1.8 closures) less if I/D contracting strategy are applied. From the RUC Table 20, the expected daily savings to road users comes out to be $526,347 and in terms of closures, the savings is expected to be $1,206,212. The expected savings in terms of agency cost comes out to be $68,400 ($156,750 per closure), based on monetary value calculation shown in Table 23.

Table 27 shows the results of Steps 1, 2, 3 and 4 in the form of upper and lower bounds of I/D before applying the Cost vs. Benefit decision making approach.

Table 27. Initial Lower and Upper Bounds of I/D (I-710)

	ΔC (JPCP)	ΔC (CRCP)	ΔC (HMA)	ΔC (MACO)	Savings to road users	Savings to the agency	Total Savings
Daily I/D	$23,764	$14,880	$10,605	$106,513	$526,347	$68,400	$594,747
Closure I/D	$54,420	$34,075	$24,285	$243,915	$1,206,212	$156,750	$1,362,962

As mentioned for the earlier I-15 Devore project, it is very clear that the incentive cap should between CAC (ΔC) and total savings (RUC + Agency Cost), but the difference between the two amounts is incredibly high and henceforth, there is a huge need to come up with certain appropriate discounting factors which will help in arriving at point based I/D estimates.

5.3 Validation of Step 5: I-15 Devore Project

Assuming the LOS for this project as E, from table 24 and 25, ADT threshold is 15,000 and average delay in seconds at any given point is 68. The AADT for this project is 100,000 which imply 85,000 vehicles are able to avoid this delay of 68 seconds when passing through any given point in the CWZ. From Table 6, the average time value for automobile and trucks is $11.51 and $27.83 per hour respectively, in the state of California. The percentage of trucks on this project is 10%.

Hence an equation can be derived on the basis of above mentioned observations: (AADT – ADT LOS Capacity Threshold) * (Percentage of Trucks * Time Value of Trucks + Percentage of Automobiles * Time Value of Automobiles) * Delay

(100,000 – 15,000) * (0.1 * 27.83 + 0.9 * 11.51) * 68 / (60 * 60) = $21,100

Hence it can be assumed that if the contractor is maintaining LOS E, the contractor is eligible to get an incentive of $21,100 in addition to the additional cost growth i.e., for this project with LOS E, following are the daily and closure I/D amounts. The same is highlighted in table 28 and 29.

Table 28. I-15 Devore Project: Point based Estimates of I/D for LOS E

	ΔC (JPCP)	JPCP Point-based I/D	ΔC (CRCP)	CRCP Point-based I/D	ΔC (HMA)	HMA Point-based I/D	ΔC (MACO)	MACO Point-based I/D
Daily I/D	$25,614	$46,714	$16,038	$37,138	$11,430	$32,530	$114,804	$135,904
Closure I/D	$76,842	$140,142	$48,114	$111,414	$34,290	$97,590	$344,412	$407,712

Table 29. Point Based Estimates of I/D for LOS D, C, B and A

	ΔC (JPCP)	JPCP Point-based I/D	ΔC (CRCP)	CRCP Point-based I/D	ΔC (HMA)	HMA Point-based I/D	ΔC (MACO)	MACO Point-based I/D
				LOS D				
Daily I/D	$25,614	$39,824	$16,038	$30,248	$11,430	$25,640	$114,804	$129,014
Closure I/D	$76,842	$119,472	$48,114	$90,744	$34,290	$76,920	$344,412	$387,042
				LOS C				
Daily I/D	$25,614	$34,609	$16,038	$25,033	$11,430	$20,425	$114,804	$123,799
Closure I/D	$76,842	$103,827	$48,114	$75,099	$34,290	$61,275	$344,412	$371,397
				LOS B				
Daily I/D	$25,614	$30,504	$16,038	$20,928	$11,430	$16,320	$114,804	$119,694
Closure I/D	$76,842	$91,512	$48,114	$62,784	$34,290	$48,960	$344,412	$359,082
				LOS A				
Daily I/D	$25,614	$28,936	$16,038	$19,360	$11,430	$14,752	$114,804	$118,126
Closure I/D	$76,842	$86,808	$48,114	$58,080	$34,290	$44,256	$344,412	$354,378

5.4 Validation of Step 5: I-710 Long Beach Project

Assuming the LOS for this project as D, from table 25 and 26, ADT threshold is 13,500 and average delay in seconds at any given point is 45. The AADT for this project is 120,000 which imply 106,500 vehicles are able to avoid this delay of 45 seconds when passing through any given point in the CWZ. From Table 6, the average time value for automobile and trucks is $11.51 and $27.83 per hour respectively, in the state of California. The percentage of trucks on this project is 5%.

Hence the equation can be derived on the basis of above mentioned observations:

(AADT – ADT) * (Percentage of Trucks * Time Value of Trucks + Percentage of Automobiles * Time Value of Automobiles) * Delay

(120,000 – 13,500) * (0.05 * 27.83 + 0.95 * 11.51) * 45 / (60 * 60) = $16,409

Hence it can be assumed that if the contractor is maintaining LOS D, the contractor is eligible to get an incentive of $16,409 in addition to the additional cost growth i.e., for this project with LOS D, following are the daily and closure I/D amounts. The same is highlighted in table 30 and 31.

Table 30. I-710 Long Beach Project: Point based Estimates of I/D for LOS D

	ΔC (JPCP)	JPCP Point-based I/D	ΔC (CRCP)	CRCP Point-based I/D	ΔC (HMA)	HMA Point-based I/D	ΔC (MACO)	MACO Point-based I/D
Daily I/D	$23,764	$40,173	$14,880	$31,289	$10,605	$27,014	$106,513	$122,922
Closure I/D	$54,420	$91,997	$34,075	$71,651	$24,285	$61,862	$243,915	$281,491

Table 31. Point Based Estimates of I/D for LOS E, C, B and A

	ΔC (JPCP)	JPCP Point-based I/D	ΔC (CRCP)	CRCP Point-based I/D	ΔC (HMA)	HMA Point-based I/D	ΔC (MACO)	MACO Point-based I/D
				LOS E				
Daily I/D	$23,764	$48,211	$14,880	$39,327	$10,605	$35,052	$106,513	$130,960
Closure I/D	$54,420	$110,403	$34,075	$90,059	$24,285	$80,269	$243,915	$299,898
				LOS C				
Daily I/D	$23,764	$34,118	$14,880	$25,234	$10,605	$20,959	$106,513	$116,867
Closure I/D	$54,420	$78,130	$34,075	$57,786	$24,285	$47,996	$243,915	$267,625
				LOS B				
Daily I/D	$23,764	$29,377	$14,880	$20,493	$10,605	$16,218	$106,513	112,126
Closure I/D	$54,420	$67,273	$34,075	$46,929	$24,285	$37,139	$243,915	$256,769
				LOS A				
Daily I/D	$23,764	$27,570	$14,880	$18,686	$10,605	$14,411	$106,513	$110,319
Closure I/D	$54,420	$63,135	$34,075	$42,791	$24,285	$33,001	$243,915	$252,631

5.5 Validation of Step 6: I-15 Devore Project

Total savings for 1 day = $243,551

Total savings for 4 days = $979,204

This amount STAs can save be finishing the project earlier by 4 days. In other words, STAs can avoid taking this money from the funding agencies which will help in saving in terms of interest charges accumulated over a period of time.

Consider this loan amount of $979,204 for a period of 10 years, with an interest rate of 5%. The formula for calculating the interest and balance charges is summarized below:

Table 32 describes the breakup of the principal amount and the interest charges.

Table 32. Breakup of the Loan Amount (I-15)

Year	Principal	Interest	Balance
2013	77454	48710	974204
2014	81326	44838	896750
2015	85393	40771	815424
2016	89662	36502	730031
2017	94146	32018	640369
2018	98853	27311	546223
2019	103795	22369	447370
2020	108985	17179	343575
2021	114434	11730	234590
2022	120156	6008	120156

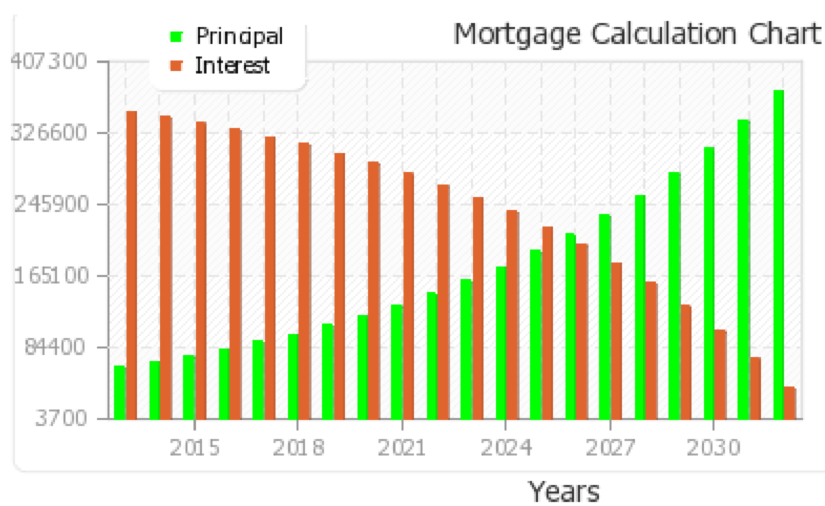


Figure 21. Amortization Depicting Principal and Interest Trend over Time

A series of cash flows can be generated using the interest column shown in the Table 32. This series of cash flows can then be used to calculate the NPV of the interest charges accumulated over a period of 10 years at an interest rate of 5% as shown in figure 21.

The NPV (upper bound) of this project comes out to be $236,550 and hence daily I/D will be $59,137.

5.6 Validation of Step 7 (I-15)

Hence using the information from Table 28, the incentive cap of this project incorporating JPCP is:

$102,456 ≤ I/D ≤ 236,550

5.7 Validation of Step 6: I-710 Long Beach Project

Total savings for 1 day = $594,747

Total savings for 4 days = $2,378,988

This amount STAs can save be finishing the project earlier by 4 days. In other words, STAs can avoid taking this money from the funding agencies which will help in saving in terms of interest charges accumulated over a period of time.

Consider this loan amount of $2,378,988 for a period of 15 years, with an interest rate of 2%. The formula for calculating the interest and balance charges is summarized below:

Table 33 describes the breakup of the principal amount and the interest charges.

Table 33. Breakup of the Loan Amount (I-710)

Year	Principal	Interest	Balance
2013	137566	47580	2378988
2014	140318	44828	2241422
2015	143124	42022	2101104
2016	145986	39160	1957980
2017	148906	36240	1811994
2018	151884	33262	1663088
2019	154922	30224	1511204
2020	158020	23965	1356282
2021	161181	27126	1198262
2022	164404	20742	1037081
2023	167692	17454	872677
2024	171046	14100	704985
2025	174467	10679	533939
2026	177957	7189	359472
2027	181516	3630	181515

A series of cash flows can be generated using the interest column shown in the Table 32. This series of cash flows can then be used to calculate the NPV of the interest charges accumulated over a period of 15 years at an interest rate of 2% as shown in table 33.

The NPV (upper bound) of this project comes out to be $355,958 and hence daily I/D will be $88,990.

5.8 Validation of Step 7 (I-710)

Hence using the information from Table 27, the incentive cap of this project incorporating JPCP is: **$95,056 ≤ I/D ≤ 355,958**

6 CONCLUSION

Accelerated innovative contracting strategies are adopted by the STAs to complete critical civil transportation projects ahead of their assigned schedule in order to minimize inconvenience to the motorists which in turn results in significant cost savings in terms of road user cost and agency cost. I/D clause in the projects are incorporated to motivate the contractors to use their ingenuity to complete the projects earlier by employing additional resources which result in additional cost growth on the part of the contractors. Therefore, incentives should be greater than the contractors additional cost for expediting construction, and at the same time in order to sound economical, incentives should be less than the total savings (Road User Cost and Agency Cost).

The decision support model proposed in the study will help assist STAs in determining realistic I/D dollar amounts by integrating schedule, total savings, and contractors additional cost. The model proposes the incorporation of Level of Service and Net Present Value concepts in order to determine contractors additional cost growth (Lower Bound) and benefits incurred in the form of road user cost and agency cost savings on the part of the transportation agencies (Upper Bound), respectively, in a more holistic manner. Validation of both the concepts was formulated with the help of case studies. The proposed model will help the STAs to determine realistic estimates of CAC in a more effective manner, and will also help in discounting the total savings to the road users and the contracting agencies.

REFERENCES

Arditi, D., and Yasamis, F. (1998). "Incentive/Disincentive Contracts: Perceptions of Owners and Contractors." *Journal of Construction Engineering and Management*, 124(5), 361-373.

Choi, K. (2008). *A New Decision-support Model for Innovative Contracting Strategies Through a Quantitative Analysis on Aspects of Project Performance*, ProQuest.

Choi, K., and Kwak, Y. H. (2012). "Decision Support Model for Incentives/Disincentives Time Cost Tradeoff." *Automation in Construction*, 21, 219-228.

Christiansen, D. L. (1987). An Analysis of the Use of Incentive/Disincentive Contracting Provisions for Early Project Completion. Special Report 212. *In Proceedings of National Conference on Corridor Traffic Management for Major Highway, Transportation Research Board, Washington, DC.*

Edwards, J., and Orfali, R. (1998). *3 Tier Client/Server at Work*, John Wiley & Sons, Inc, New York, USA, ISBN 0471315028.

Ellis Jr, R. D., Pyeon, J. H., Herbsman, Z. J., Minchin, E., & Molenaar, K. (2007). Evaluation of Alternative Contracting Techniques on FDOT Construction Projects, *Final Report, FDOT, Tallahassee, Florida*.

Ellis, R. D., & Pyeon, J. (2005). A Study of Simulation-Based Contract Incentives and Disincentives Usage. In *Construction Research Congress: Broadening Perspectives, American Society of Civil Engineers, San Diego, CA.*

Federal Highway Administration (FHWA). (1989). “Incentive/Disincentive (I/D) for Early Completion.” *Tech. Advisory T 5090.10*, Federal Highway Administration (FHWA), Washington, D.C.

Gillespie, J. S. (1998). *Estimating User Costs as a Basis for Incentive/Disincentive Amounts in Highway Construction Contracts*. Virginia Transportation Research Council.

Herbsman, Z. J., Chen, W. T., and Epstein, W. C. (1995). "Time is Money: Innovative Contracting Methods in Highway Construction." *Journal of Construction Engineering and management*, 121(3), 273-281.

Honek, K., Azar, E., & Menassa, C. C. (2011). Recession Effects in United States Public Sector Construction Contracting: Focus on the American Recovery and Reinvestment Act of 2009. *Journal of Management in Engineering*, *28*(4), 354-361.

Ibarra, C., Trietsch, G., and Dudek, C. (2002). "Strategies Used by State DOT's to Accelerate Highway Construction Projects." *Texas A&M University-Department of Civil Engineering*.

Jaraiedi, M., Plummer, R. W., and Aber, M. S. (1995). "Incentive/Disincentive Guidelines for Highway Construction Contracts." *Journal of Construction Engineering and management*, 121(1), 112-120.

Jiang, Y., Chen, H., and Li, S. (2010). "Determination of Contract Time and Incentive and Disincentive Values of Highway Construction Projects." *International Journal of Construction Education and Research*, 6(4), 285-302.

Khanum, T., Hossain, M., and Schieber, G. (2006). Influence of Traffic Inputs on Rigid Pavement Design Analysis Using Mechanistic-Empirical Pavement Design Guide. In *Transportation Research Board 85th Annual Meeting* (No. 06-2621).

Labi, S., Lamptey, G., Konduri, S., & Sinha, K. C. (2005). Part 1: Pavement Management: Analysis of Long-Term Effectiveness of Thin Hot-Mix Asphaltic Concrete Overlay Treatments. *Transportation Research Record: Journal of the Transportation Research Board*, *1940*(1), 1-12.

Lee, E. B., and Ibbs, C. (2005). "Computer Simulation Model: Construction Analysis for Pavement Rehabilitation Strategies." *Journal of Construction Engineering and management*, 131(4), 449-458.

Lee, E. B., Kim, C., & Harvey, J. T. (2006). Implementation of Automated Travel-Time Information and Public Reaction on Urban Highway Rehabilitation. *Journal of Transportation Engineering*, *132*(10), 808-816.

Lee, S. J., Akisetty, C. K., & Amirkhanian, S. N. (2008). The Effect of Crumb Rubber Modifier (CRM) on the Performance Properties of Rubberized Binders in HMA Pavements. *Construction and Building Materials*, *22*(7), 1368-1376.

Liu, Y. T., & Hu, H. (2011). Functional Modeling for an Integrated Pipeline Integrity Management System Using IDEF0 Approach. In *Proceedings of the 1st International Conference on Transportation Information and Safety* (pp. 1848-1855). ASCE.

Muga, H. E., Mukherjee, A., Mihelcic, J. R., & Kueber, M. J. (2009). An Integrated Assessment of Continuously Reinforced and Jointed Plane Concrete Pavements. *Journal of Engineering, Design and Technology*, *7*(1), 81-98.

Orndoff, C., & Papkov, G. (2012). Effect of the 2009 American Recovery and Reinvestment Act (ARRA) on Civil Engineering. *Journal of Professional Issues in Engineering Education and Practice*, *137*(1), 2-9.

Pyeon, J. H., & Lee, E. B. (2012). *Systematic Procedures to Determine Incentive/Disincentive Dollar Amounts for Highway Transportation Construction Projects* (No. CA-MTI-12-2908), VA, USA.

Scurfield, R., Sleet, D., Mohan, D., Hyder, A. A., Jarawan, E., & Mathers, C. D. (Eds.). (2004). *World Report on Road Traffic Injury Prevention*. World Health Organization, Geneva.

Shr, J. F., and Chen, W. T. (2004). "Setting Maximum Incentive for Incentive/Disincentive Contracts for Highway Projects." *Journal of Construction Engineering and Management*, 130(1), 84-93.

Sillars, D. N., & Leray, J. P. A. (2006). *Incentive/Disincentive Contracting Practices for Transportation Projects*. Alternative Project Delivery, Procurement, and Contracting Methods for Highways: pp. 129-152. ASCE Press. Washington, DC.

Sun, C., Edara, P., & Mackley, A. (2013). In Milton the Disincentive is Lost: Refocusing on Liquidated Damages in Incentive/Disincentive Contracts. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 5(3),136 -141.

Talluri, S., & Paul Yoon, K. (2000). A Cone-Ratio DEA Approach for AMT Justification. *International Journal of Production Economics*, 66(2), 119-129.

Waltman, W. D., & Presley, A. (1993). Reading & Critiquing an IDEF0 Model. *Automation & Robotics Research. Institute, Fort Worth Texas. Julho de1993*.

Winston, C., & Langer, A. (2006). The Effect of Government Highway Spending on Road Users' Congestion Costs. *Journal of Urban Economics, 60(3), 463-483*.

Uhlmeyer, J., & Russell, M. (2013). *Dowel Bars for New and Existing Concrete Pavements* (No. 13-01-0001702). Construction Division State Materials Laboratory , Washington State Department of Transportation.

APPENDIX

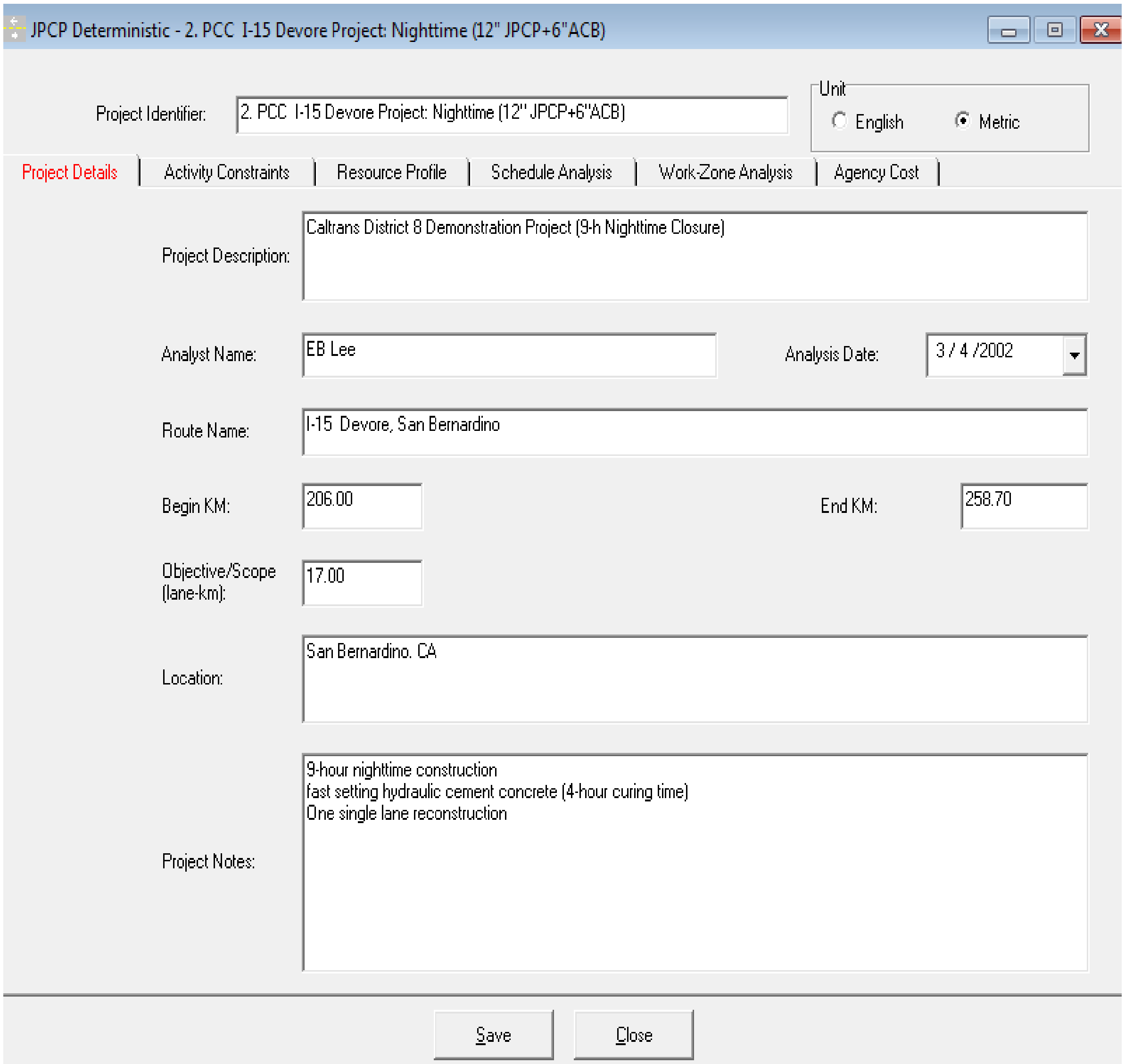


Figure 22. CA4PRS Project Details

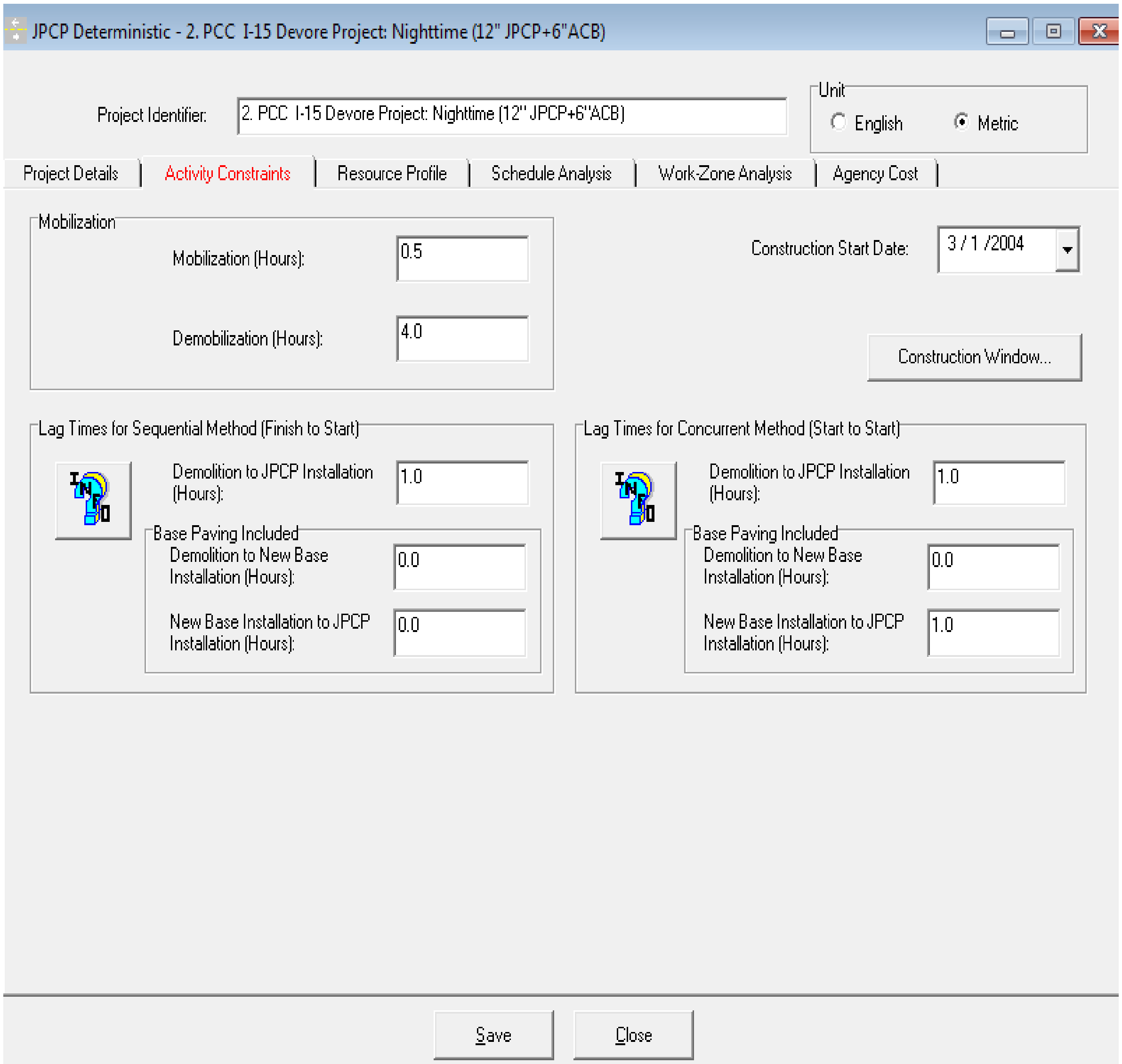


Figure 23. CA4PRS Activity Constraints

Figure 24. CA4PRS Construction Windows

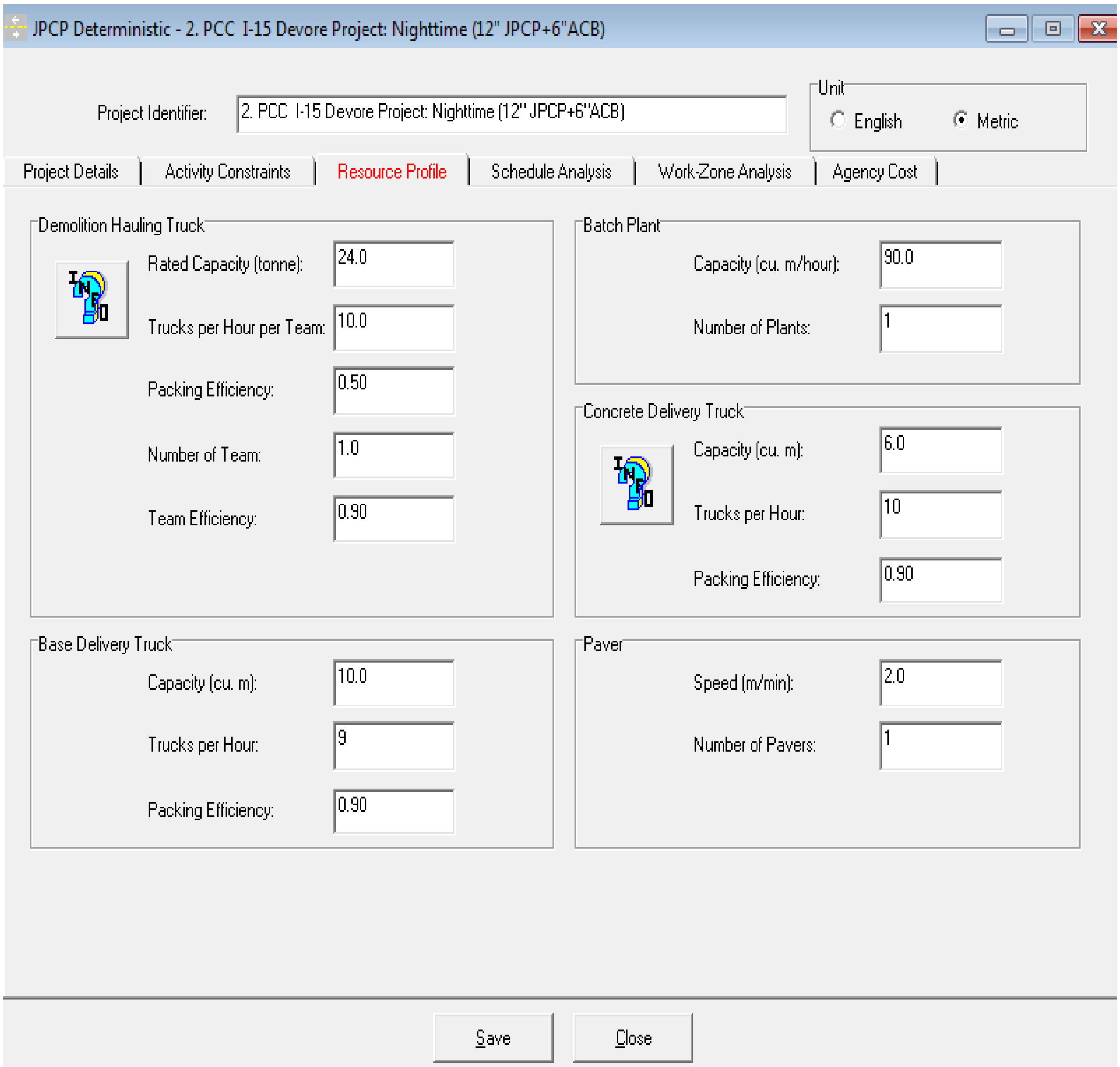


Figure 25. CA4PRS Resource Profile

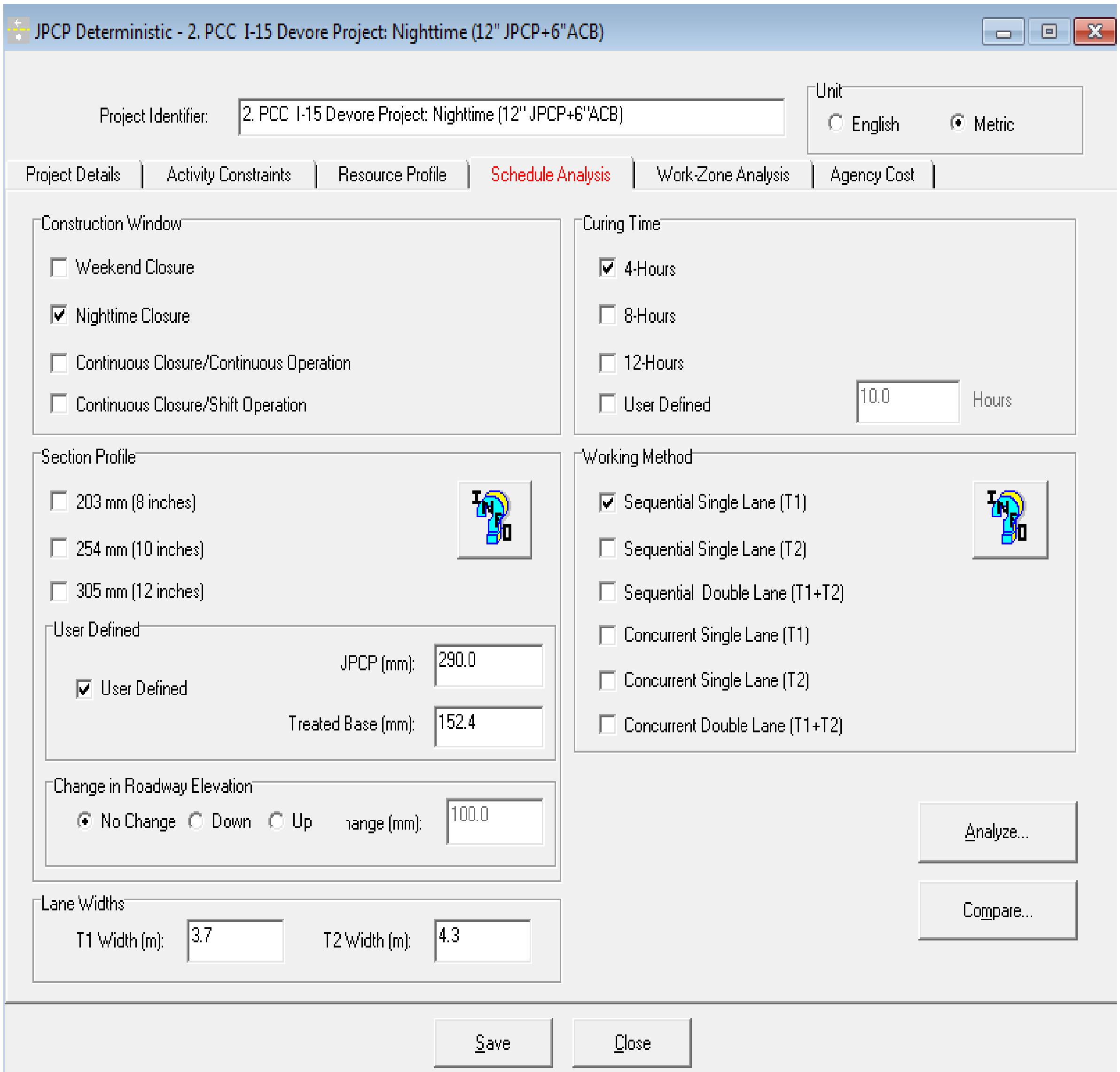


Figure 26. CA4PRS Schedule Analysis

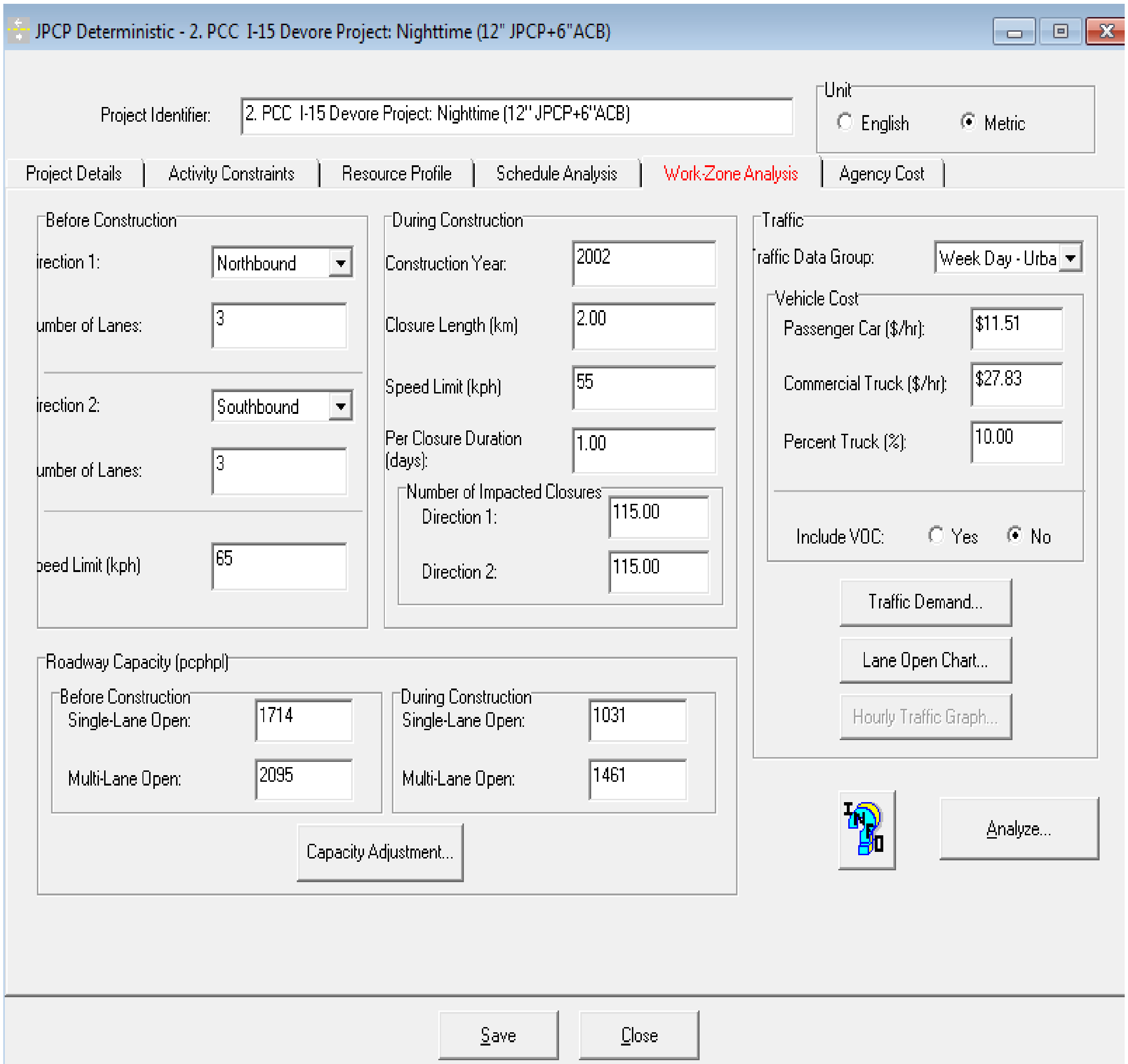
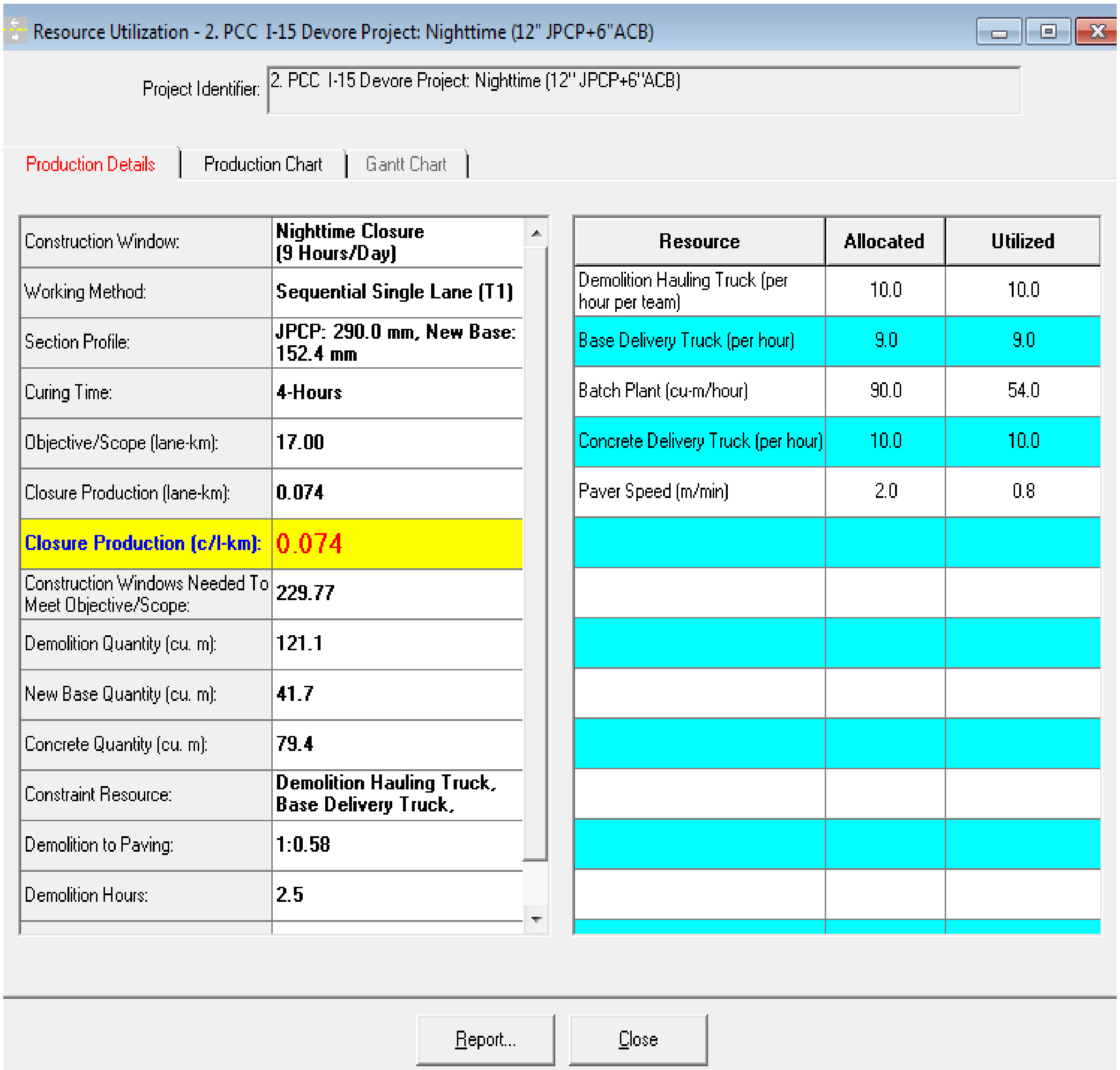


Figure 27. CA4PRS Work-Zone Analysis



Construction Window:	Nighttime Closure (9 Hours/Day)
Working Method:	Sequential Single Lane (T1)
Section Profile:	JPCP: 290.0 mm, New Base: 152.4 mm
Curing Time:	4-Hours
Objective/Scope (lane-km):	17.00
Closure Production (lane-km):	0.074
Closure Production (c/l-km):	0.074
Construction Windows Needed To Meet Objective/Scope:	229.77
Demolition Quantity (cu. m):	121.1
New Base Quantity (cu. m):	41.7
Concrete Quantity (cu. m):	79.4
Constraint Resource:	Demolition Hauling Truck, Base Delivery Truck,
Demolition to Paving:	1:0.58
Demolition Hours:	2.5

Resource	Allocated	Utilized
Demolition Hauling Truck (per hour per team)	10.0	10.0
Base Delivery Truck (per hour)	9.0	9.0
Batch Plant (cu-m/hour)	90.0	54.0
Concrete Delivery Truck (per hour)	10.0	10.0
Paver Speed (m/min)	2.0	0.8

Figure 28. CA4PRS Construction Windows

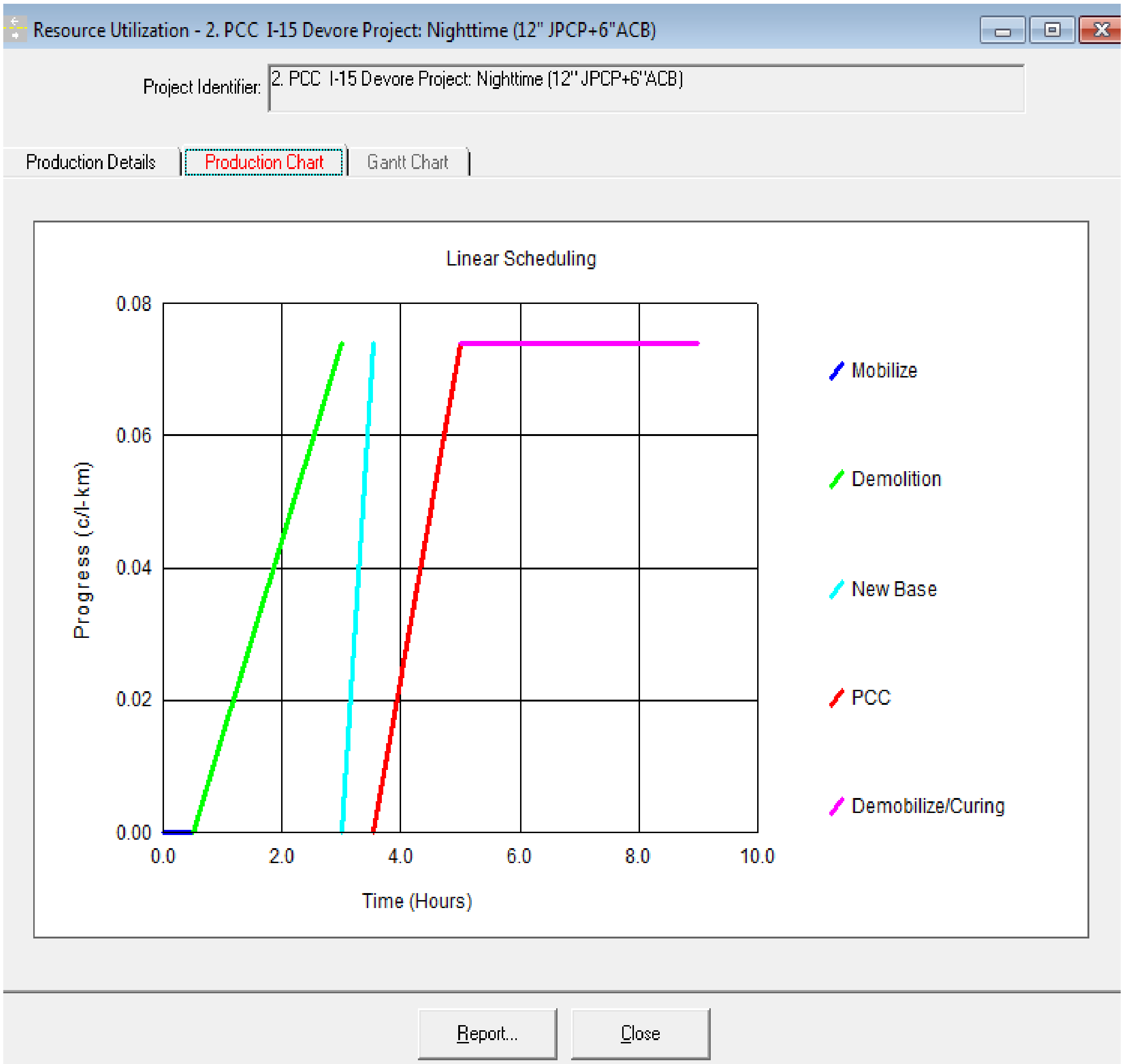


Figure 29. CA4PRS Production Chart